2008-12

Performance analysis of an alternative link-16/JTIDS waveform transmitted over a channel with pulse-noise

Wei, Ho Kah

Monterey California. Naval Postgraduate School

http://hdl.handle.net/10945/3840

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

PERFORMANCE ANALYSIS OF AN ALTERNATIVE LINK-16/JTIDS WAVEFORM TRANSMITTED OVER A CHANNEL WITH PULSE-NOISE INTERFERENCE

by

Ho Kah Wei

December 2008

Thesis Advisor: Clark Robertson
Second Reader: Frank Kragh

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** December 2008	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE: Performance Analysis of an Alternative Link-16/JTIDS Waveform Transmitted Over a Channel with Pulse-Noise Interference.	**5. FUNDING NUMBERS**
6. AUTHOR Ho Kah Wei	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8.PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

The Joint Tactical Information Distribution System (JTIDS) is a hybrid frequency-hopped, direct sequence spread spectrum system that utilizes a (31, 15) Reed-Solomon (RS) code and cyclical code-shift keying modulation for the data packets, where each encoded symbol consists of five bits. The primary drawback to JTIDS is the limited data rate. In this thesis, an alternative waveform consistent with the existing JTIDS waveform but with twice the data rate is analyzed. The system to be considered also uses (31, 15) RS encoding, but each pair of five-bit symbols at the output of the RS encoder undergoes serial-to-parallel conversion to two five-bit symbols, which are then independently transmitted on the in-phase and quadrature component of the carrier using 32-ary orthogonal signals with a diversity of two. In this thesis, only coherent detection is considered. The performance obtained with the alternative JTIDS waveform is compared with the existing JTIDS waveform when only additive white Gaussian noise (AWGN) is present as well as when pulse-noise interference (PNI) is also present. Errors-and-erasures decoding (EED), errors only decoding and perfect side information (PSI) are also considered. Based on the analyses, we conclude that the alternative JTIDS waveform performs better in AWGN as well as when PNI is also present for typical values of information bit error probability (i.e., $P_b = 10^{-5}$ to 10^{-7}). In AWGN, at $P_b = 10^{-5}$, the alternative JTIDS waveform has a 2.3 dB gain in information bit energy over white noise ratio (E_C / N_O) as compared to the original JTIDS waveform. In AWGN and PNI, when $E_C / N_O = 5$ dB and $P_b = 10^{-5}$ for both waveforms, the alternative JTIDS waveform is superior to the original JTIDS waveform with a gain in information bit energy over pulse-noise ratio (E_C / N_I) of 5.6 dB and 5.4 dB for $\rho = 0.2$ and 0.1, respectively, where ρ is the fraction of time the PNI is present. The use of EED does not improve the performance of the alternative JTIDS waveform in AWGN and PNI as compared to errors-only decoding. With PSI, the alternative JTIDS waveform performs significantly better than the original JTIDS waveform with EED. At $P_b = 10^{-6}$ and for $\rho = 1$, the alternative JTIDS waveform shows an improvement of 5.4 dB in E_C / N_I over the original JTIDS waveform and the gain improves for $\rho < 1$.

14. SUBJECT TERMS Link-16/JTIDS, (31, 15) Reed-Solomon (RS) coding, 32-ary Orthogonal signaling, Additive White Gaussian Noise (AWGN), Pulse-Noise Interference (PNI), Errors-and-Erasures decoding (EED).	**15. NUMBER OF PAGES** 66
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

PERFORMANCE ANALYSIS OF AN ALTERNATIVE LINK-16/JTIDS WAVEFORM TRANSMITTED OVER A CHANNEL WITH PULSE-NOISE INTERFERENCE

Ho Kah Wei
Major, Republic of Singapore Air Force
B.Eng. (EE), National University of Singapore, 1999

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 2008

Author: Ho Kah Wei

Approved by: R. Clark Robertson
Thesis Advisor

Frank Kragh
Second Reader

Jeffrey B. Knorr
Chairman, Department of Electrical and Computer Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The Joint Tactical Information Distribution System (JTIDS) is a hybrid frequency-hopped, direct sequence spread spectrum system that utilizes a (31, 15) Reed-Solomon (RS) code and cyclical code-shift keying modulation for the data packets, where each encoded symbol consists of five bits. The primary drawback to JTIDS is the limited data rate. In this thesis, an alternative waveform consistent with the existing JTIDS waveform but with twice the data rate is analyzed. The system to be considered also uses (31, 15) RS encoding, but each pair of five-bit symbols at the output of the RS encoder undergoes serial-to-parallel conversion to two five-bit symbols, which are then independently transmitted on the in-phase and quadrature component of the carrier using 32-ary orthogonal signals with a diversity of two. In this thesis, only coherent detection is considered. The performance obtained with the alternative JTIDS waveform is compared with the existing JTIDS waveform when only additive white Gaussian noise (AWGN) is present as well as when pulse-noise interference (PNI) is also present. Errors-and-erasures decoding (EED), errors-only decoding and perfect side information (PSI) are also considered.

Based on the analyses, we conclude that the alternative JTIDS waveform performs better in AWGN as well as when PNI is also present for typical values of information bit error probability (i.e., $P_b = 10^{-5}$ to 10^{-7}). In AWGN, at $P_b = 10^{-5}$, the alternative JTIDS waveform has a 2.3 dB gain in information bit energy over white noise ratio (E_C / N_O) as compared to the original JTIDS waveform. In AWGN and PNI, when $E_C / N_O = 5$ dB and $P_b = 10^{-5}$ for both waveforms, the alternative JTIDS waveform is superior to the original JTIDS waveform with a gain in information bit energy over pulse-noise ratio (E_C / N_I) of 5.6 dB and 5.4 dB for $\rho = 0.2$ and 0.1, respectively, where ρ is the fraction of time the PNI is present. The use of EED does not improve the performance of the alternative JTIDS waveform in AWGN and PNI as compared to errors-only decoding. With PSI, the alternative JTIDS waveform performs significantly better than the original

JTIDS waveform with EED. At $P_b = 10^{-6}$ and for $\rho = 1$, the alternative JTIDS waveform shows an improvement of 5.4 dB in E_C / N_I over the original JTIDS waveform and the gain improves for $\rho < 1$.

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

Network Centric Warfare (NCW) is central to the military strategies of many modern military forces today. NCW, when realized to its full potential, enables all field and headquarter units to have full situational awareness of the battlefield. The key technology enabling NCW is the tactical data link. Tactical data links are the means by which real-time information can be exchanged between the various military units to achieve information superiority. The Joint Tactical Information Distribution System (JTIDS)/Link-16 is an advanced tactical datalink system used by the military forces of a number of countries around the world. It provides digital communications for both voice and data for command and control, relative positioning and identification.

Link-16/JTIDS operates in the L-band and employs time-division multiple access for bandwidth sharing. In order for Link-16/JTIDS to operate reliably in the battlefield environment, Link-16/JTIDS uses frequency-hopping, direct sequence spread spectrum, error detection and correction, and data encryption to create a secure data network.

Link-16/JTIDS uses cyclic code-shift keying (CCSK) for symbol modulation and minimum shift-keying (MSK) for chip modulation. The data is first encoded using a (31, 15) Reed Solomon code. The coded five-bit symbols are then interleaved and modulated using CCSK to produce 32-chip symbols which are exclusive-ored with a 32-chip pseudo-random sequence before the chips are transmitted using MSK.

In this thesis, an alternative waveform consistent with the existing JTIDS waveform but with twice the data rate is analyzed. The system to be considered also uses (31, 15) RS encoding, but each pair of five-bit symbols at the output of the RS encoder undergoes serial-to-parallel conversion to two five-bit symbols, which are then independently transmitted on the in-phase and quadrature components of the carrier using 32-ary orthogonal signals with a diversity of two. In this thesis, only coherent detection is considered. The performance obtained with the alternative JTIDS waveform is compared with the existing JTIDS waveform when only additive white Gaussian noise (AWGN) is

present as well as when pulse-noise interference (PNI) is present. Errors-and-erasures decoding (EED), errors-only decoding and perfect side information (PSI) are also considered.

Based on the analyses, we conclude that the alternative JTIDS waveform performs better in AWGN as well as when PNI is also present for typical values of information bit error probability (i.e., P_b = 10^{-5} to 10^{-7}). In AWGN, at $P_b = 10^{-5}$, the alternative JTIDS waveform has a 2.3 dB gain in information bit energy over white noise ratio (E_C / N_O) as compared to the original JTIDS waveform. In AWGN and PNI, when $E_C / N_O = 5$ dB and $P_b = 10^{-5}$ for both waveforms, the alternative JTIDS waveform is superior to the original JTIDS waveform with a gain in information bit energy over pulse-noise ratio (E_C / N_I) of 5.6 dB and 5.4 dB for $\rho = 0.2$ and 0.1, respectively, where ρ is the fraction of time the PNI is present. The use of EED does not improve the performance of the alternative JTIDS waveform in AWGN and PNI as compared to errors-only decoding. With PSI, the alternative JTIDS waveform performs significantly better than the original JTIDS waveform with EED. At $P_b = 10^{-6}$ and for $\rho = 1$, the alternative JTIDS waveform shows an improvement of 5.4 dB in E_C / N_I over the original JTIDS waveform and the gain improves for $\rho < 1$.

ACKNOWLEDGMENTS

I would like to express my utmost gratitude to Professor Clark Robertson of the Naval Postgraduate School, Monterey, California, for his guidance, patience and contribution to the successful completion of this thesis.

I would also like to thank Assistant Professor Frank Kragh for his time and patience in serving as my second reader and reviewing this thesis.

I would also like to express thanks and appreciation to my lovely wife, Hui Ling, for her endless support, encouragement and belief in me.

Finally, I would like to thank my sponsor, Republic of Singapore Air Force, for giving me the opportunity to further my studies and experience living in the United States.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. OVERVIEW

Network Centric Warfare (NCW) is central to the military strategies of many modern military forces today. NCW, when realized to its full potential, enables all field and headquarter (HQ) units to have full situational awareness of the battlefield. The key technology enabling NCW is the use of tactical data links. Tactical data links are the means by which real time information can be exchanged amongst various military units to achieve information superiority.

The Joint Tactical Information Distribution System (JTIDS)/Link-16 is an advanced tactical datalink system used by the military forces of a number of countries around the world. It provides digital communications for both voice and data for command and control, relative positioning and identification. [1]

Link-16/JTIDS operates at the L-band frequencies and employs time division multiple access for bandwidth sharing. Link-16/JTIDS uses cyclic code-shift keying (CCSK) and minimum-shift keying (MSK) to modulate digital data. The data is first encoded using a (31, 15) Reed Solomon (RS) code. The coded five-bit symbols are then interleaved and modulated using CCSK to produce 32-chip pseudo-random sequences. The primary drawback to Link16/JTIDS is the limited data rate that can be achieved. [1]

B. THESIS OBJECTIVE

Enhancements to JTIDS have been introduced to alleviate problems arising from its basic design architecture. One such enhancement is the Link-16 Enhanced Throughput (LET) capability that is intended to increase throughput. LET works by replacing the spread spectrum and RS encoding with a newer RS/convolutional coding scheme which can adapt to the required link capacity. LET can provide 3.33, 5.08, 7.75, 9.0, or 10.25 times more throughput than the basic JTIDS modulation but does so at the expense of both link robustness and transmission range. Thus, LET may be unusable in most combat environments [1]. Other papers on JTIDS, [2], [3] and [4], included a comparison of a CCSK waveform with an orthogonal waveform. In [3], an analysis of different forward

error correction (FEC) techniques for high-rate direct sequence spread spectrum was examined. In [4], an analytical approximation for the probability of symbol error of CCSK was derived, but the performance was shown in [5] to be optimistic by about 2 dB.

The alternative JTIDS waveform to be investigated in this thesis employs an M-ary orthogonal signal with (n, k) RS coding. The data is first encoded using a RS code, and the coded symbol stream undergoes serial-to-parallel conversion to two five-bit symbol streams that are each independently modulated using an M-ary orthogonal signal with M-chip baseband waveforms on both the in-phase (I) and quadrature (Q) components of the carrier. In addition, a sequential diversity of two is assumed, so the alternative waveform is a potential alternative for the JTIDS double-pulse structure. In order to be consistent with the original JTIDS waveform, 32-ary orthogonal signaling with 32-chip baseband waveforms and a (31, 15) RS code are chosen. Only coherent detection is considered in this thesis. The objective of this thesis is to investigate this alternative JTIDS waveform that is consistent with the existing JTIDS waveform but with twice the data rate and potentially better performance in both an AWGN as well as an AWGN plus pulse-noise interference (PNI) environment. To the best of the author's knowledge, the analysis of an alternative JTIDS waveform obtained by replacing CCSK with an M-ary orthogonal signal and taking into account PNI has not been previously investigated for the JTIDS double-pulse structure.

C. THESIS OUTLINE

This thesis is organized into five chapters. The introduction to this thesis is covered in Chapter I. In Chapter II, the background concepts necessary for the development of the alternative JTIDS waveform are discussed. The results of the performance analysis of the alternative JTIDS waveform in both AWGN only as well as AWGN plus PNI are presented in Chapter III. The performance comparison between the alternative and the original JTIDS waveforms in both AWGN only as well as AWGN plus PNI is presented in Chapter IV. Finally, the conclusions to this thesis based on the results in Chapters III and IV are stated in Chapter V.

II. BACKGROUND

In this chapter, some of the background knowledge and concepts required for the subsequent analysis of the alternative JTIDS waveform are introduced.

A. *M*-ARY ORTHOGONAL SIGNALS

For *M*-ary communication systems, one of M unique signals, $s_m(t), m = 1, 2, ..., M$, is transmitted in order to represent symbol m. Each symbol represents k bits where $M = 2^k$. An *M*-ary orthogonal signal can be received either coherently (the receiver requires the phase of the received signal) or noncoherently (the receiver does not require the phase of the received signal). This type of receiver can be implemented either with a bank of M multipliers and low pass filters or with a bank of M matched filters [6]. In this thesis, only coherent detection is considered.

The waveform of an *M*-ary orthogonal signal when only AWGN is present is represented by

$$s_T(t) = \sqrt{2}A_c c_m(t)\cos(2\pi f_c t + \theta_i) + n(t) \tag{2.1}$$

where f_c is the carrier frequency, $\sqrt{2}A_c$ is the received signal amplitude, $n(t)$ is AWGN with PSD $N_O/2$, the phase difference is known for coherent detection and $c_m(t)$, $m = 1, 2, ..., M$, is a baseband waveform that represents symbol m. In this thesis, the baseband waveform is taken to be a non-return-to zero polar sequence of pulses with unity amplitude. A block diagram of a coherent *M*-ary orthogonal baseband waveform demodulator is shown in Figure 1.

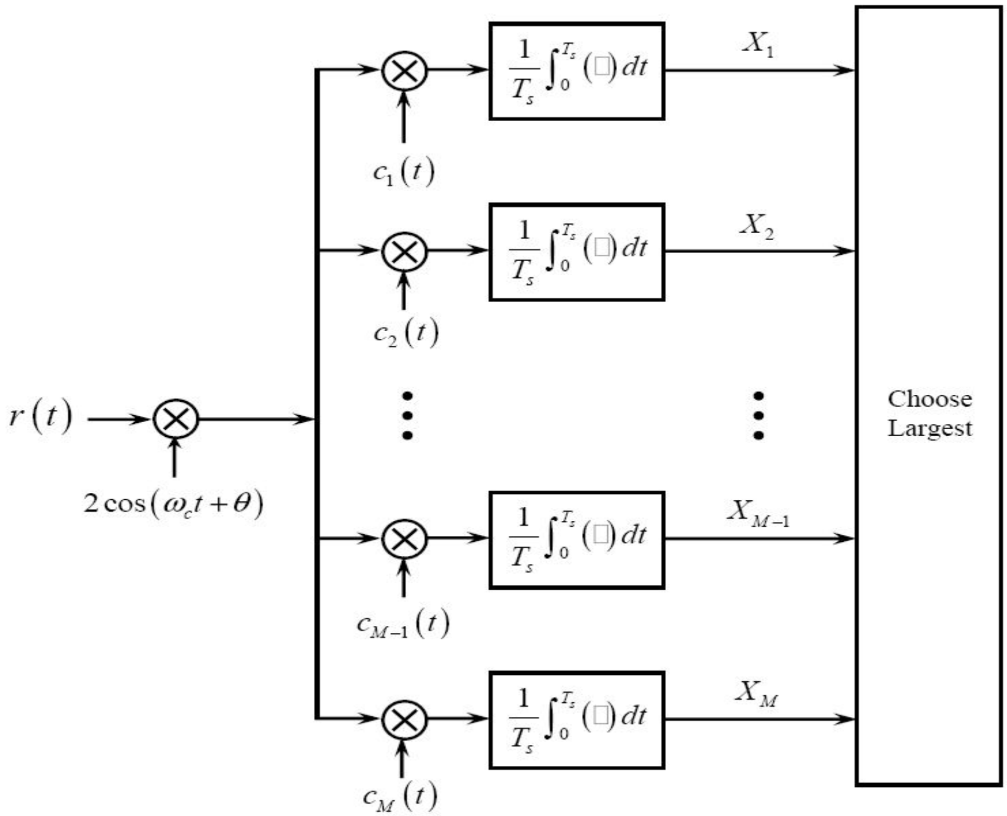

Figure 1. Block diagram of a coherent *M*-ary orthogonal baseband waveform demodulator with no diversity [From [6]].

It can be shown that the integrator outputs $x_m(iT_S)$ for each branch of the receiver can be represented as the independent Gaussian random variables X_m, $m = 1, 2, ..., M$. The conditional probability density functions for the random variables X_m, $m = 1, 2, ..., M$, that represent the integrator outputs when the noise is modeled as Gaussian are [6]

$$f_{X_m}\left(x_m \mid m\right) = \frac{1}{\sqrt{2\pi}\sigma_{X_m}} \exp\left[\frac{-\left(x_m - \sqrt{2}A_c\right)^2}{2\sigma_{X_m}{}^2}\right] \text{ for } m \le M \tag{2.2}$$

and

$$f_{X_n}\left(x_n \mid m,\, n \ne m\right) = \frac{1}{\sqrt{2\pi}\sigma_{X_m}} \exp\left[\frac{-x_n{}^2}{2\sigma_{X_m}{}^2}\right] \tag{2.3}$$

when the signal corresponding to symbol m is transmitted and

$$\sigma_{X_1}{}^2 = \sigma_{X_2}{}^2 = \ldots = \sigma_{X_M}{}^2 = \sigma^2 = N_O / T_s. \tag{2.4}$$

The mean of X_m is given by

$$\begin{aligned}\overline{X_m} &= \frac{2\sqrt{2}A_c}{T_s}\int_0^{T_s} c_m(t)c_n(t)\cos^2(2\pi f_c t + \theta_i)dt \\ &= \begin{cases}\sqrt{2}A_c & for\, n=m \\ 0 & for\, n\neq m\end{cases}\end{aligned} \tag{2.5}$$

B. PERFORMANCE OF *M*-ARY ORTHOGONAL SIGNALING IN AWGN

When AWGN is present with power spectral density $N_O / 2$, the probability of channel symbol error for coherent *M*-ary orthogonal signaling in AWGN is [6]

$$p_s = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} e^{\left(\frac{-u^2}{2}\right)}\left\{1-\left[1-Q\left(u+\sqrt{\frac{2E_s}{N_O}}\right)\right]^{M-1}\right\}du \tag{2.6}$$

where E_s is the average energy per channel symbol and is equal to $A_c{}^2 T_s$, where $A_c{}^2$ is the average received signal power, T_s is the symbol duration and $Q(\bullet)$ is the Q-function. Equation (2.6) will be used to obtain the probability of information symbol and information bit error for the alternative JTIDS waveform in the next chapter.

C. PERFORMANCE IN AWGN WITH PULSED-NOISE INTERFERENCE

For military applications, where hostile jamming is expected, we have to also consider the effect of PNI on the performance of the system. In this thesis, we evaluate the performance of the alternative JTIDS waveform in both AWGN and PNI.

When a channel is affected by AWGN, the noise signal that arrives at the receiver is uniformly spread across the spectrum and time-independent. This may not be true if PNI is present. In this thesis, the AWGN and PNI are assumed to be statistically independent, and the PNI is modeled as Gaussian noise. When AWGN and PNI are both present, the total noise power at the receiver integrator outputs is given by

$$\sigma_X^2 = \sigma_{WG}^2 + \sigma_I^2 \tag{2.7}$$

where $\sigma_{WG}^2 = N_O / T_s$ and $\sigma_I^2 = N_I / \rho T_s$, $N_I / 2$ is the PNI power spectral density when ρ = 1, and ρ is the fraction of time that an interferer is switched on. When ρ=1, the interferer is continuously on and is referred to as barrage noise interference.

D. PERFORMANCE WITH DIVERSITY

JTIDS employs several techniques to increase immunity to hostile interference. Diversity is one such technique used. In JTIDS, diversity is implemented as a simple repetition code, referred to as either the single-pulse (no diversity) or the standard double-pulse (STDP) structure (sequential diversity of two). For the STDP, the same symbol is transmitted twice at different carrier frequencies, providing redundancy. In order for the diversity to be effective, each redundant symbol must be received independently [7].

When diversity of order L is employed and each diversity reception is independent of the others, the probability that i of L diversity receptions are affected by PNI, where ρ represents the fraction of time that the channel is affected by PNI, is represented as [8]

$$\Pr(i \text{ of } L \text{ pulses jammed}) = \binom{L}{i} \rho^i (1-\rho)^{L-i} \tag{2.8}$$

where there are $\binom{L}{i}$ different ways in which i of L diversity receptions can be received in error.

Consequently, the probability of channel symbol error for a system with diversity L in the presence of PNI is

$$p_s = \sum_{i=0}^{L} [\Pr(i \text{ of } L \text{ signals jammed})\, p_s(i)] \tag{2.9}$$

where $p_s(i)$ is the conditional probability of channel symbol error given that i symbols experience PNI.

Substituting (2.8) into (2.9), we get

$$p_s = \sum_{i=0}^{L}\left[\binom{L}{i}\rho^i(1-\rho)^{L-i}\, p_s(i)\right] \tag{2.10}$$

The challenge is to find $p_s(i)$ for the various conditions such as no side information, perfect side information, and so on.

E. FORWARD ERROR CORRECTION CODING

For JTIDS, the forward error correction (FEC) used is a (31, 15) RS code, a linear, non-binary block code. In order to maintain consistency with the original JTIDS waveform, the alternative JTIDS waveform also employs (31, 15) RS coding for error detection and correction. For non-binary codes, symbols are generated instead of bits, where each symbol represents *m* bits and the number of different symbols required are $M = 2^m$. An (n, k) RS encoder, takes *k* information symbols (mk information bits) and generates *n* coded symbols (mn coded bits) [9].

For (*n*, *k*) RS coding, the probability of decoder error, or block error, is upper bounded by the sum of the probabilities that a received codeword differs from the correct codeword by *i* symbols for $i > t$ [9]. Therefore,

$$P_E \le \sum_{i=t+1}^{n}\binom{n}{i}p_s^{\,i}\left(1-p_s\right)^{n-i} \tag{2.11}$$

or

$$P_E \le 1-\sum_{i=0}^{t}\binom{n}{i}p_s^{\,i}\left(1-p_s\right)^{n-i} \tag{2.12}$$

where the inequality holds for either a perfect code or a bounded distance decoder, *t* is the symbol error correcting capability of the code and p_s is the probability of coded, or channel, symbol error and is given by (2.10).

For RS codes and *M*-ary orthogonal modulation with $M = 2^m$, we obtain the probability of information bit error as [9]

$$P_b \approx \frac{n+1}{2n^2}\sum_{i=t+1}^{n} i\binom{n}{i}p_s^{\,i}\left(1-p_s\right)^{n-i}. \tag{2.13}$$

F. ERRORS-AND-ERASURES DECODING

Errors-and-erasures decoding (EED) is the simplest form of soft decision decoding, an alternative to hard decision decoding, and is easily implemented. The concept behind EED is such that for symbols that are received ambiguously, an erasure is declared. Thus, in binary erasure decoding, the output of the demodulator is not binary but ternary, and the three possible outputs are bit 1, bit 0, and erasure (e). Suppose that a received code word has a single erased bit. Now all valid code words are separated by a Hamming distance of at least $d_{\min}-1$. In general, given e erasures in a received code word, all valid code words are separated by a Hamming distance of at least $d_{\min}-e$. Hence, the effective minimum distance between valid code words is [9]

$$d_{\min_{eff}} = d_{\min} - e. \tag{2.14}$$

Therefore, the number of errors in the non-erased bits of the code word that can be corrected is [9]

$$t_e = \frac{1}{2}\lfloor d_{\min} - e - 1 \rfloor. \tag{2.15}$$

where $\lfloor x \rfloor$ means rounding x down. Thus, a total of t_e errors and e erasures can be corrected as long as

$$2t_e + e < d_{\min}. \tag{2.16}$$

Hence, twice as many erasures as errors can be corrected. Intuitively, this makes sense because we have more information about the erasures; the locations of the erasures are known, but the locations of the errors are not.

For error-and-erasures decoding, the probability that there are a total of i errors and j erasures in a block of n symbols is given by [9]

$$\Pr(i,j) = \binom{n}{i}\binom{n-i}{j} p_s^i p_e^j p_c^{n-i-j} \tag{2.17}$$

where each symbol is assumed to be received independently, p_e is the probability of channel symbol erasure, p_s is the probability of channel symbol error, and the probability of correct channel symbol detection is given by p_c. The probability of channel symbol error can be obtained from [9]

$$p_s = 1 - p_e - p_c. \tag{2.18}$$

Since a block error does not occur as long as $d_{\min} > 2i + j$, then from (2.17) the probability of correct block decoding is bounded by

$$P_C \geq \Pr(d_{\min} > 2i + j) = \sum_{i=0}^{t} \binom{n}{i} p_s^i \sum_{j=0}^{d_{\min}-1-2i} \binom{n-i}{j} p_e^j p_c^{n-i-j} \tag{2.19}$$

In this case, the probability of block error is given by

$$P_E = 1 - P_C \tag{2.20}$$

Substituting (2.19) into (2.20), we get

$$P_E \leq 1 - \sum_{i=0}^{t} \binom{n}{i} p_s^i \sum_{j=0}^{d_{\min}-1-2i} \binom{n-i}{j} p_e^j p_c^{n-i-j} \tag{2.21}$$

Using the average of the upper and lower bound on the probability of symbol error given that a *block* error has occurred, we can approximate the probability of information symbol error as [9]

$$P_s \approx \frac{k+1}{2k} P_E \tag{2.22}$$

The probability of information *bit* error can be obtained by [6]

$$P_b = \frac{M}{2(M-1)} P_s \tag{2.23}$$

G. PERFECT-SIDE INFORMATION

For a system with a diversity of *L*, where the diversity receptions are received independently, perfect-side information (PSI) can be considered as a means to reduce to the effect of PNI. For a diversity of two, when both received symbols in the repetitive pulses are unaffected by PNI, they are combined and demodulated as usual. If either of the diversity receptions are affected by PNI, the receiver discards the PNI-affected symbol and makes a decision based on the remaining diversity reception affected only by AWGN. When both diversity receptions are affected by PNI, the receiver combines the two receptions and makes a decision. PSI requires at least a diversity of two and can improve system performance in a PNI environment where $\rho < 1$.

H. CHAPTER SUMMARY

In this chapter, *M*-ary orthogonal signals were introduced and the background and concepts necessary to examine the performance of the alternative JTIDS waveform were addressed. The concept of forward error correction coding as well as the concept of errors-and-erasures decoding was also introduced. In the next chapter, the performance of the alternative JTIDS waveform for both AWGN as well as AWGN plus PNI are analyzed. The performance obtained with both EED and PSI are also analyzed.

III. PERFORMANCE ANALYSIS OF THE ALTERNATIVE JTIDS WAVEFORM

In this chapter, we examine the performance of the alternative JTIDS waveform by analyzing the bit error versus the signal-to-noise ratio for both AWGN as well as AWGN plus PNI. The performance obtained with both EED and PSI is also analyzed. For Link-16/JTIDS, the data rate for the double-pulse structure is half that of the single-pulse structure. Furthermore, the average energy per bit, both channel and data, is doubled when the double-pulse structure is used. That is, Link-16/JTIDS is not a constant average energy per bit system when it changes between the single- and the double-pulse structure. In this thesis, comparisons are made based on the average energy per bit per pulse, not the total average energy per bit.

A. PERFORMANCE IN AWGN

The probability of channel symbol error for *M*-ary orthogonal signaling is given by (2.6). For sequential diversity L with linear, soft combining, L pulses are transmitted for every channel symbol, where each pulse represents the same symbol. Hence, the received energy-per-channel symbol is L times the energy-per-pulse; i.e., $E_s = LE_p$. In addition, each pulse represents m bits. Thus, the received energy-per-pulse is the product of m, r and the average energy-per-bit-pulse; i.e., $E_p = rmE_C$, where E_C is the average information bit energy in a pulse and $r = k/n$ is the code rate. Thus, (2.6) can be modified to obtain an expression for channel symbol error probability for *M*-ary orthogonal signaling with (n, k) RS coding and having diversity L in terms of E_C as

$$p_s = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{\left(\frac{-u^2}{2}\right)} \left\{ 1 - \left[1 - Q\left(u + \sqrt{\frac{2LrmE_C}{N_O}} \right) \right]^{M-1} \right\} du \qquad (3.1)$$

where $r = k/n$ is the code rate, E_C is the average information bit energy in a pulse and soft decision demodulation with linear combining is assumed.

Since $L = 2$, $M = 32$ and $m = 5$, (3.1) simplifies to

$$p_s = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{\left(\frac{-u^2}{2}\right)} \left\{ 1 - \left[1 - Q\left(u + \sqrt{\frac{20rE_C}{N_O}} \right) \right]^{31} \right\} du. \tag{3.2}$$

We can obtain the probability of information bit error using (2.13), repeated here for convenience:

$$P_b \approx \frac{n+1}{2n^2} \sum_{i=t+1}^{n} i \binom{n}{i} p_s^{\,i} \left(1 - p_s\right)^{n-i}. \tag{3.3}$$

The performance of 32-ary orthogonal signaling with (31, 15) RS coding for both no diversity and a diversity of two is shown in Figure 2. At $P_b = 10^{-5}$, the double-pulse structure (i.e., diversity of two) has a 3 dB improvement in E_C / N_O as compared to the single-pulse structure (i.e., no diversity).

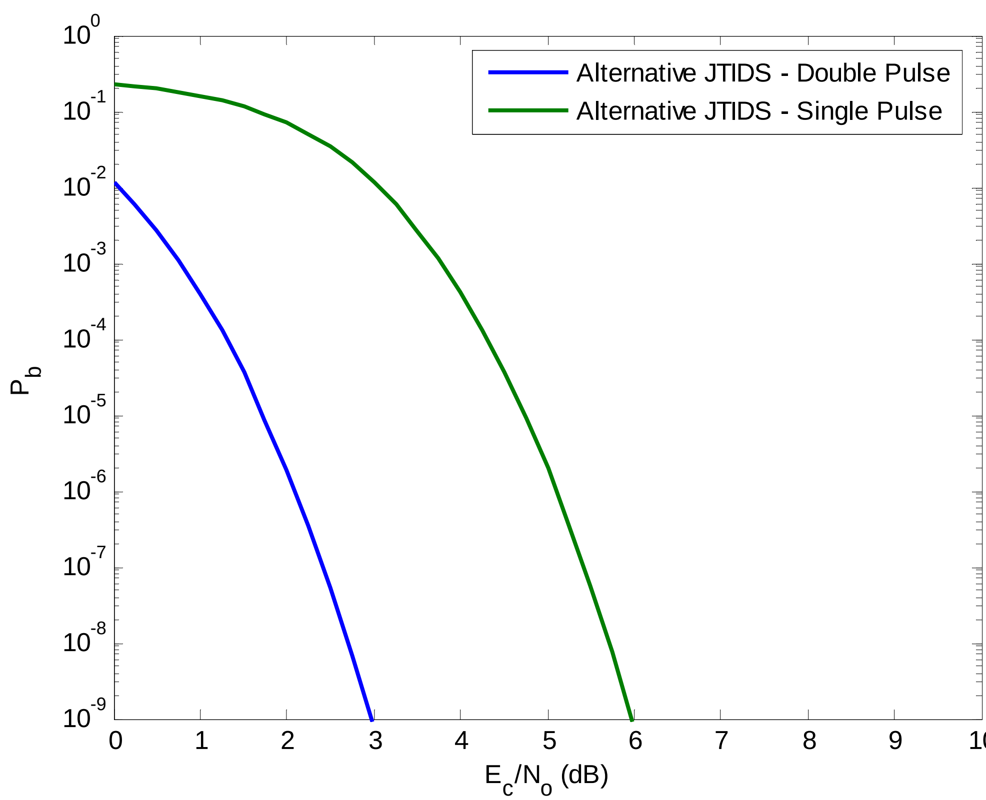

Figure 2. Performance of 32-ary orthogonal signaling with (31, 15) RS encoding for both the single-pulse and the double-pulse structure in AWGN.

B. PERFORMANCE IN AWGN AND PNI

For a channel with both AWGN and PNI, the probability of channel symbol error for a diversity of two is given by

$$p_s = \sum_{i=0}^{2}\left[\binom{2}{i}\rho^i(1-\rho)^{2-i}\, p_s(i)\right] \tag{3.4}$$

where $p_s(i)$ is the conditional probability of channel symbol error given that i symbols experience PNI.

The conditional probability density functions for the random variables X_m, where $m=1,2,...,M$, that represent the decision variables obtained by linear, soft combining of the integrator outputs are given by

$$f_{X_m}\left(x_m \mid m,i\right)=\frac{1}{\sqrt{2\pi}\sigma_m(i)}\exp\left[\frac{-\left(x_m-2\sqrt{2}A_c\right)^2}{2\sigma_m{}^2(i)}\right] \tag{3.5}$$

and

$$f_{X_n}\left(x_n \mid m,\, n\neq m,i\right)=\frac{1}{\sqrt{2\pi}\sigma_m(i)}\exp\left[\frac{-x_n{}^2}{2\sigma_m{}^2(i)}\right] \tag{3.6}$$

where

$$\sigma_m^2(i)=i\sigma_T^2+(2-i)\sigma_o^2 \tag{3.7}$$

and

$$\sigma_T^2=\sigma_I^2+\sigma_o^2 \tag{3.8}$$

With $\sigma_o^2=N_O/T_s$ and $\sigma_I^2=N_I/\rho T_s$ and substituting (3.8) into (3.7), we obtain

$$\sigma_m^2(i)=\frac{iN_I}{\rho T_s}+\frac{2N_O}{T_s} \tag{3.9}$$

Comparing (3.5) through (3.9) to (2.2) through (2.4), we can modify (2.6) to obtain the conditional probability of channel symbol error as

$$p_s(i)=\int_{-\infty}^{\infty}\frac{1}{\sqrt{2\pi}\sigma_m(i)}e^{\frac{-(x_1-2\sqrt{2}A_c)^2}{2\sigma_m^2(i)}}\left(1-\left[1-Q\left(\frac{x_1}{\sigma_m(i)}\right)\right]^{M-1}\right)dx_1 \tag{3.10}$$

which can be expressed as

$$p_s(i)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} e^{\frac{-u^2}{2}}\left(1-\left[1-Q\left(u+2\sqrt{\frac{2E_p}{\frac{iN_I}{\rho}+2N_O}}\right)\right]^{M-1}\right)du \tag{3.11}$$

Since $E_p = rmE_C$, the conditional probability of channel symbol error with coding is given by

$$p_s(i)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} e^{\frac{-u^2}{2}}\left(1-\left[1-Q\left(u+2\sqrt{\frac{2rm}{\frac{i}{\rho}\gamma_I^{-1}+2\gamma_c^{-1}}}\right)\right]^{M-1}\right)du \tag{3.12}$$

where $\gamma_I = E_C/N_I$ and $\gamma_c = E_C/N_O$.

The probability of channel symbol error is obtained by substituting (3.12) into (3.4). The probability of information bit error is then obtained by substituting (3.4) into (2.13), which was repeated in (3.3).

The performance for different values of ρ with E_C/N_O = 2.45 dB is shown in Figure 3. The E_C/N_O is chosen to be 2.45 dB since this yields P_b = 10^{-7} at E_C/N_I = 20 dB. It can be seen that at P_b = 10^{-5}, varying ρ from 1 to 0.05 does not degrade the receiver performance significantly as compared to barrage jamming (ρ = 1). The degradation is less than 1 dB. It can also be observed that very small ρ (0.02) results in a better performance as compared to larger ρ when E_C/N_I is small. This is logical since, from (3.4), for very small values of ρ, the $i=0$ term (i.e., the term that corresponds to when no pulses are affected by the pulse-noise interference) dominates the summation.

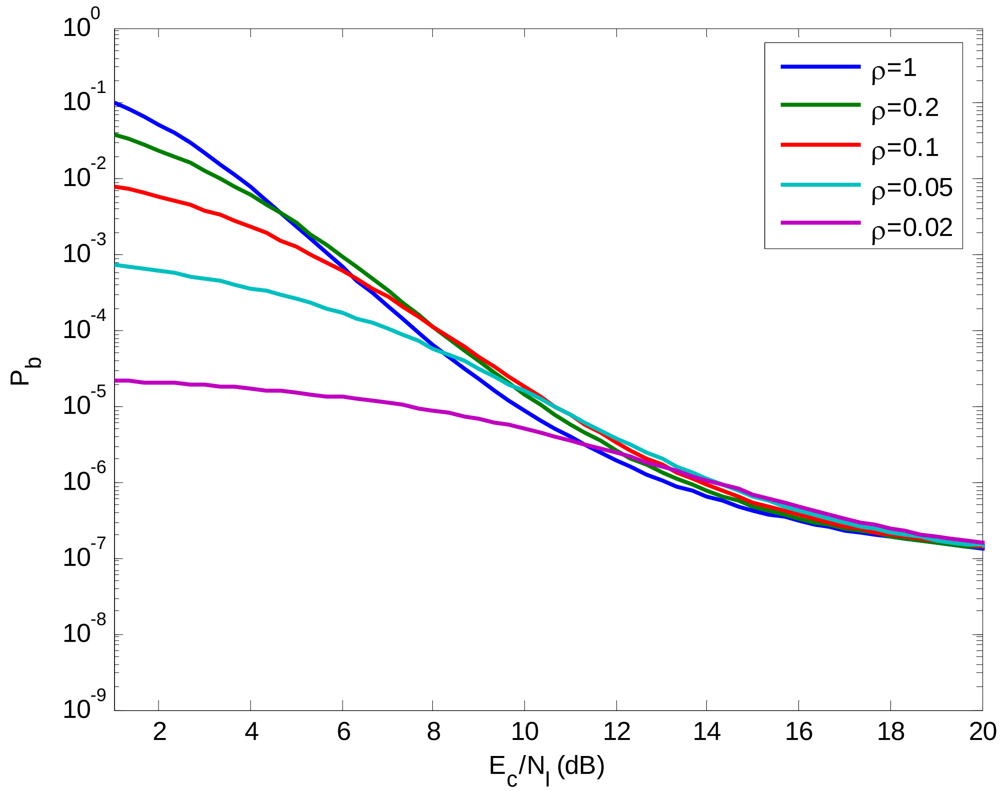

Figure 3. Performance of 32-ary orthogonal signaling with (31, 15) RS encoding in an AWGN plus PNI environment for different ρ with $E_C/N_O = 2.45$ dB.

In Figure 4, we let $E_C / N_O = 3$ dB, and P_b approaches 10^{-9} at $E_C / N_I = 25$ dB. In this case, the degradation in performance due to PNI as compared to barrage jamming increases to about 1.1 dB at $P_b = 10^{-5}$. However, the absolute performance for various values of ρ improves by about 2 dB compared to when $E_C / N_O = 2.45$ dB. In Figure 5, we let $E_C / N_O = 10$ dB. In this case, the degradation due to PNI as compared to barrage jamming increases to about 3.3 dB at $P_b = 10^{-5}$. However, the absolute performance for the values of ρ improves by more than 5 dB compared to when $E_C / N_O = 2.45$ dB. The results for Figures 3, 4 and 5 are summarized in Table 1.

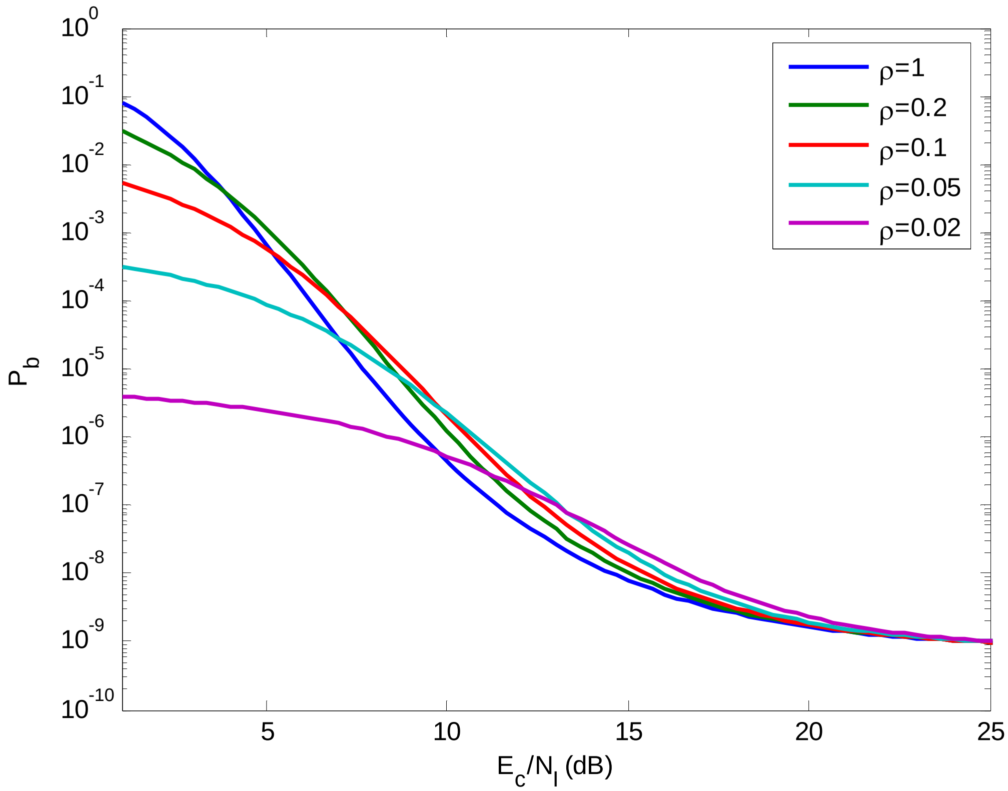

Figure 4. Performance of 32-ary orthogonal signaling with (31, 15) RS encoding in an AWGN plus PNI environment for different ρ with $E_C/N_O = 3$ dB.

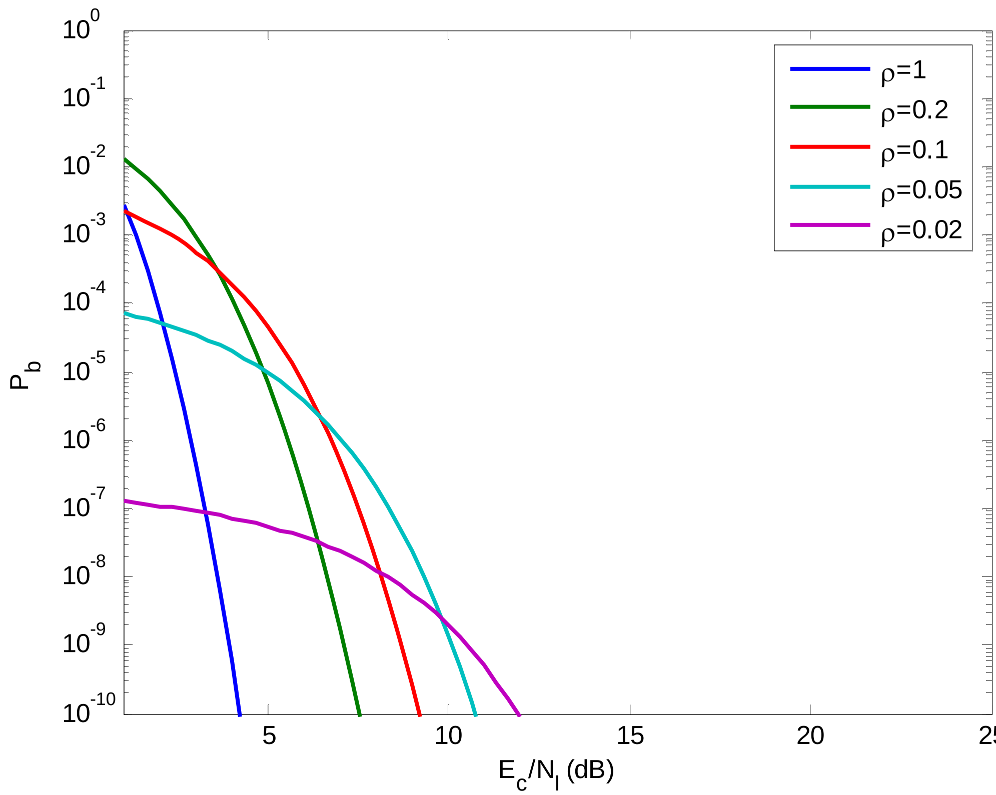

Figure 5. Performance of 32-ary orthogonal signaling with (31, 15) RS encoding in an AWGN plus PNI environment for different ρ with $E_C/N_O = 10$ dB.

Table 1. Performance results at $P_b = 10^{-5}$ for $E_C/N_O = 2.45$ dB, $E_C/N_O = 3$ dB and $E_C/N_O = 10$ dB in an AWGN plus PNI environment for different values of ρ.

ρ	$E_C/N_O = 2.45$ dB	$E_C/N_O = 3$ dB	$E_C/N_O = 10$ dB
	E_C/N_I (dB)	E_C/N_I (dB)	E_C/N_I (dB)
1	9.9	7.7	2.5
0.2	10.4	8.5	4.9
0.1	10.7	8.8	5.8

C. PERFORMANCE IN AWGN AND PNI WITH EED

At the demodulator, the receiver has to decide which of the M symbols was received or decide that it cannot make a decision with sufficient confidence. If the output of each integrator is $V_T > X_i$, $i = 1, 2, ..., M$, then the receiver cannot decide with sufficient confidence, and the symbol is erased.

Without loss of generality, we assume that the signal representing symbol '1' is transmitted. With errors-and-erasures demodulation, if symbol '1' is transmitted, then the probability of channel symbol erasure p_e and probability of correct channel symbol detection p_c are [6]

$$p_e = \Pr(V_T > X_1 \cap V_T > X_2 \cap V_T > X_3 \cap ... \cap V_T > X_M \mid 1) \tag{3.13}$$

and

$$p_c = \Pr(X_1 > X_2 \cap X_1 > X_3 \cap ... \cap X_1 > X_M \mid 1, X_1 > V_T) \tag{3.14}$$

respectively. The probability of channel symbol error can be obtained by substituting (3.13) and (3.14) into

$$p_s = 1 - p_e - p_c. \tag{3.15}$$

From (3.13), the probability of symbol erasure is given by [6]

$$p_e = \int_{-\infty}^{V_T}\int_{-\infty}^{V_T}\int_{-\infty}^{V_T}...\int_{-\infty}^{V_T} f_{X_1 X_2 ... X_M}\left(x_1, x_2, ..., x_M \mid 1\right) dx_1 dx_2 dx_3 ... dx_M \tag{3.16}$$

where $f_{X_1 X_2 ... X_M}\left(x_1, x_2, ..., x_M \mid 1\right)$ represents the joint probability density function of the random variables that model the branch outputs. Since the random variables that model the branch outputs are independent, (3.16) can be written as

$$\begin{aligned} p_e &= \int_{-\infty}^{V_T} f_{X_1}\left(x_1 \mid 1\right) dx_1 \int_{-\infty}^{V_T} f_{X_2}\left(x_2 \mid 1\right) dx_2 \\ &\times \int_{-\infty}^{V_T} f_{X_3}\left(x_3 \mid 1\right) dx_3 ... \int_{-\infty}^{V_T} f_{X_M}\left(x_M \mid 1\right) dx_M. \end{aligned} \tag{3.17}$$

Since $\int_{-\infty}^{V_T} f_{X_2}\left(x_2 \mid 1\right) dx_2 = \int_{-\infty}^{V_T} f_{X_3}\left(x_3 \mid 1\right) dx_3 = ... = \int_{-\infty}^{V_T} f_{X_M}\left(x_M \mid 1\right) dx_M$, we can simplify (3.17) to

$$p_e = \left[\int_{-\infty}^{V_T} f_{X_1}\left(x_1 \mid 1\right) dx_1\right]\left[\int_{-\infty}^{V_T} f_{X_2}\left(x_2 \mid 1\right) dx_2\right]^{M-1} \tag{3.18}$$

The conditional probability density functions for the random variables X_m, where $m = 1, 2, ..., M$, that represent the integrator outputs in an AWGN and PNI environment are given by (3.5) and (3.6). Substituting (3.5) and (3.6) into (3.18), we obtain the conditional probability of channel symbol erasure given that *i* diversity receptions experience PNI as

$$p_e(i) = \left[\int_{-\infty}^{V_T} \frac{1}{\sqrt{2\pi}\sigma_m(i)} \exp\left[\frac{-\left(x_1 - 2\sqrt{2}A_c\right)^2}{2\sigma_m^2(i)} \right] dx_1 \right] \times \left[\int_{-\infty}^{V_T} \frac{1}{\sqrt{2\pi}\sigma_m(i)} \exp\left[\frac{-x_2{}^2}{2\sigma_m^2(i)} \right] dx_2 \right]^{M-1} \tag{3.19}$$

which can be evaluated to obtain

$$p_e(i) = \left[1 - Q\left(\frac{V_T - 2\sqrt{2}A_c}{\sigma_m(i)} \right) \right] \left[1 - Q\left(\frac{V_T}{\sigma_m(i)} \right) \right]^{M-1}. \tag{3.20}$$

Defining $V_T = a(2\sqrt{2}A_c)$, where $0 < a < 1$, and together with (3.9), we get the conditional probability of channel symbol erasure given that *i* diversity receptions experience PNI as

$$p_e(i) = \left[1 - Q\left((a-1)2\sqrt{\frac{2rmE_C}{\frac{iN_I}{\rho} + 2N_O}} \right) \right] \left[1 - Q\left(2a\sqrt{\frac{2rmE_C}{\frac{iN_I}{\rho} + 2N_O}} \right) \right]^{M-1} \tag{3.21}$$

where ρ represents the fraction of time the channel is affected by PNI, *r* is the code rate and E_C is the average information bit energy-per-pulse.

The probability of channel symbol erasure for a diversity of two with EED is obtained by substituting (3.21) into (3.4) to obtain

$$p_e = \sum_{i=0}^{2}\left[\binom{2}{i}\rho^i(1-\rho)^{2-i}\right]$$
$$\times\left[1-Q\left((a-1)2\sqrt{\frac{2rmE_C}{\frac{iN_I}{\rho}+2N_O}}\right)\right] \quad (3.22)$$
$$\times\left[1-Q\left(2a\sqrt{\frac{2rmE_C}{\frac{iN_I}{\rho}+2N_O}}\right)\right]^{M-1}.$$

Similarly, we can derive an expression for the conditional probability of correct channel symbol detection. From (3.14), we get

$$p_c(i) = \int_{V_T}^{\infty}\left[\int_{-\infty}^{x_1}\int_{-\infty}^{x_1}...\int_{-\infty}^{x_1} f_{X_1X_2...X_M}\left(x_1,x_2,...,x_M \mid 1\right)dx_2dx_3...dx_M\right]dx_1 \quad (3.23)$$

Since the random variables X_m, where $m = 1,2,...,M$, are independent, (3.23) can be written as

$$p_c(i) = \int_{V_T}^{\infty} f_{X_1}\left(x_1 \mid 1\right)$$
$$\times\left[\int_{-\infty}^{x_1} f_{X_2}\left(x_2 \mid 1\right)dx_2\int_{-\infty}^{x_1} f_{X_3}\left(x_3 \mid 1\right)dx_3...\int_{-\infty}^{x_1} f_{X_M}\left(x_M \mid 1\right)dx_M\right]dx_1 \quad (3.24)$$

Since $\int_{-\infty}^{x_1} f_{X_2}\left(x_2 \mid 1\right)dx_2 = \int_{-\infty}^{x_{1T}} f_{X_3}\left(x_3 \mid 1\right)dx_3 = ... = \int_{-\infty}^{x_1} f_{X_M}\left(x_M \mid 1\right)dx_M$, (3.24) can be simplified to

$$p_c(i) = \int_{V_T}^{\infty} f_{X_1}\left(x_1 \mid 1\right)\times\left[\int_{-\infty}^{x_1} f_{X_2}\left(x_2 \mid 1\right)dx_2\right]^{M-1}dx_1 \quad (3.25)$$

The conditional probability density functions for the random variables X_m, where $m = 1,2,...,M$, that represent the soft combining of the integrator outputs in an AWGN and PNI environment are given by (3.5) and (3.6). Substituting (3.5) and (3.6) into (3.25), we obtain the conditional probability of correct channel symbol detection given that *i* diversity receptions experience PNI as

$$p_c(i) = \int_{V_T}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_m(i)} e^{\left[\frac{-\left(x_1 - 2\sqrt{2}A_c\right)^2}{2\sigma_m^2(i)}\right]} \left[\int_{-\infty}^{x_1} \frac{1}{\sqrt{2\pi}\sigma_m(i)} \exp\left(\frac{-x_2{}^2}{2\sigma_m^2(i)}\right) dx_2\right]^{M-1} dx_1 \quad (3.26)$$

which can be partially evaluated to obtain

$$p_c(i) = \int_{V_T}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_m(i)} e^{\left[\frac{-\left(x_1 - 2\sqrt{2}A_c\right)^2}{2\sigma_m^2(i)}\right]} \left[1 - Q\left(\frac{x_1}{\sigma_m(i)}\right)\right]^{M-1} dx_1. \quad (3.27)$$

Letting $u = \left(x_1 - \sqrt{2}A_c\right) / \sigma$, we get

$$p_c(i) = \int_{\frac{V_T - 2\sqrt{2}A_c}{\sigma_m(i)}}^{\infty} \frac{1}{\sqrt{2\pi}} e^{\left[\frac{-u^2}{2}\right]} \left[1 - Q\left(u + \frac{2\sqrt{2}A_c}{\sigma_m(i)}\right)\right]^{M-1} du. \quad (3.28)$$

Substituting $V_T = a(2\sqrt{2}A_c)$ and (3.9) into (3.28), we obtain the conditional probability of correct channel symbol detection given that i diversity receptions experience PNI as

$$p_c(i) = \frac{1}{\sqrt{2\pi}} \int_{-(1-a)2\sqrt{\frac{2rmE_C}{\frac{iN_I}{\rho}+2N_o}}}^{\infty} e^{\left[\frac{-u^2}{2}\right]} \times \left[1 - Q\left(u + 2\sqrt{\frac{2rmE_C}{\frac{iN_I}{\rho} + 2N_O}}\right)\right]^{M-1} du. \quad (3.29)$$

Substituting (3.29) into (3.4), we obtain the probability of correct channel detection for a diversity of two with EED as

$$\begin{aligned} p_c = \sum_{i=0}^{2} & \left[\binom{2}{i} \rho^i (1-\rho)^{2-i}\right. \\ & \times \left.\left[\frac{1}{\sqrt{2\pi}} \int_{-(1-a)2\sqrt{\frac{2rmE_C}{\frac{iN_I}{\rho}+2N_o}}}^{\infty} e^{\left[\frac{-u^2}{2}\right]} \times \left[1 - Q\left(u + 2\sqrt{\frac{2rmE_C}{\frac{iN_I}{\rho} + 2N_O}}\right)\right]^{M-1} du\right]\right]. \end{aligned} \quad (3.30)$$

As previously mentioned, the probability of channel symbol error with EED is

$$p_s = 1 - p_e - p_c \quad (3.31)$$

where p_e is given by (3.22) and p_c is given by (3.30).

For errors-and-erasures decoding, the probability of block error is given by [6]

$$P_E \le 1 - \left[\sum_{i=0}^{t} \binom{n}{i} p_s^i \sum_{j=0}^{d_{\min}-1-2i} \binom{n-i}{j} p_e^j p_c^{n-i-j} \right] \tag{3.32}$$

where (3.22), (3.30) and (3.31) are substituted into (3.32). Finally, the probability of information symbol error and information bit error can be obtained using (2.22) and (2.23), respectively.

The results for 32-ary orthogonal signaling with (31, 15) RS coding and EED and a diversity of two in PNI for different values of a are shown in Figures 6 and 7, where E_C/N_O is 3 dB and 15 dB, respectively. It is observed that there are no significant differences in performance for $0.1 \le a \le 0.6$. However, performance degrades for $a > 0.6$ regardless of the value of E_C/N_O. This is expected since when a reaches a large value, many more received symbols are erased, overwhelming the erasure correction ability of the RS code. Since there are no significant differences in performance for $0.1 \le a \le 0.6$, we shall use $a = 0.6$ for subsequent analysis involving EED.

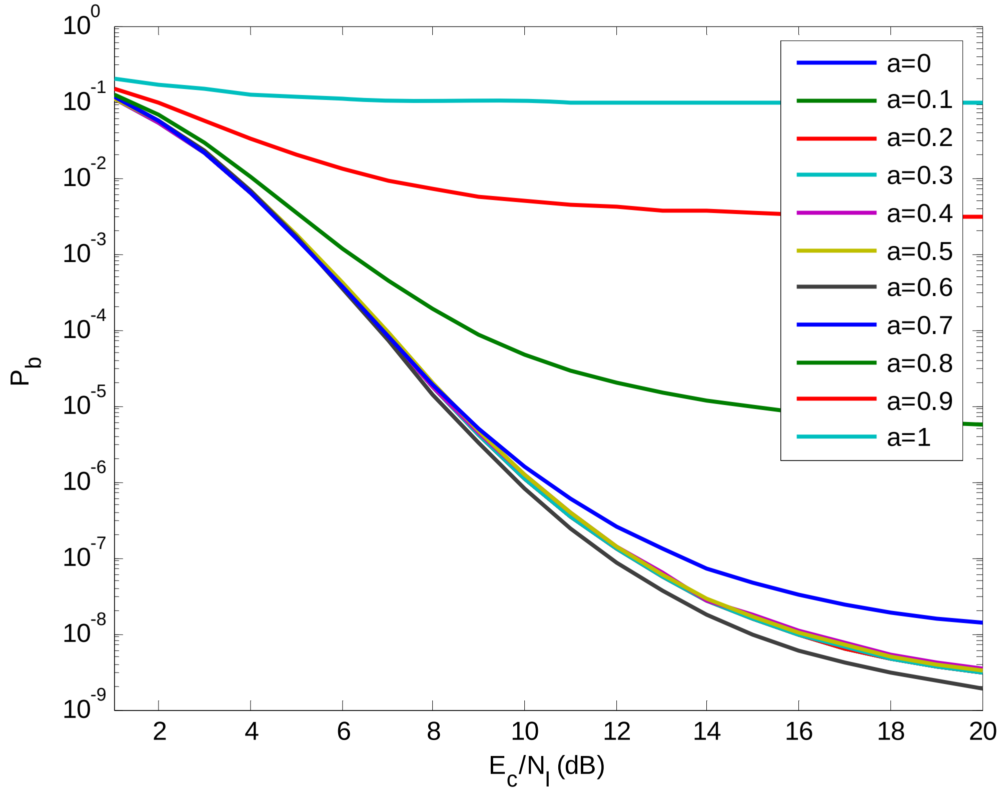

Figure 6. Performance of 32-ary orthogonal signaling with (31, 15) RS encoding and EED in AWGN plus PNI with $\rho = 0.5$ and $E_C/N_O = 3$ dB for different values of a.

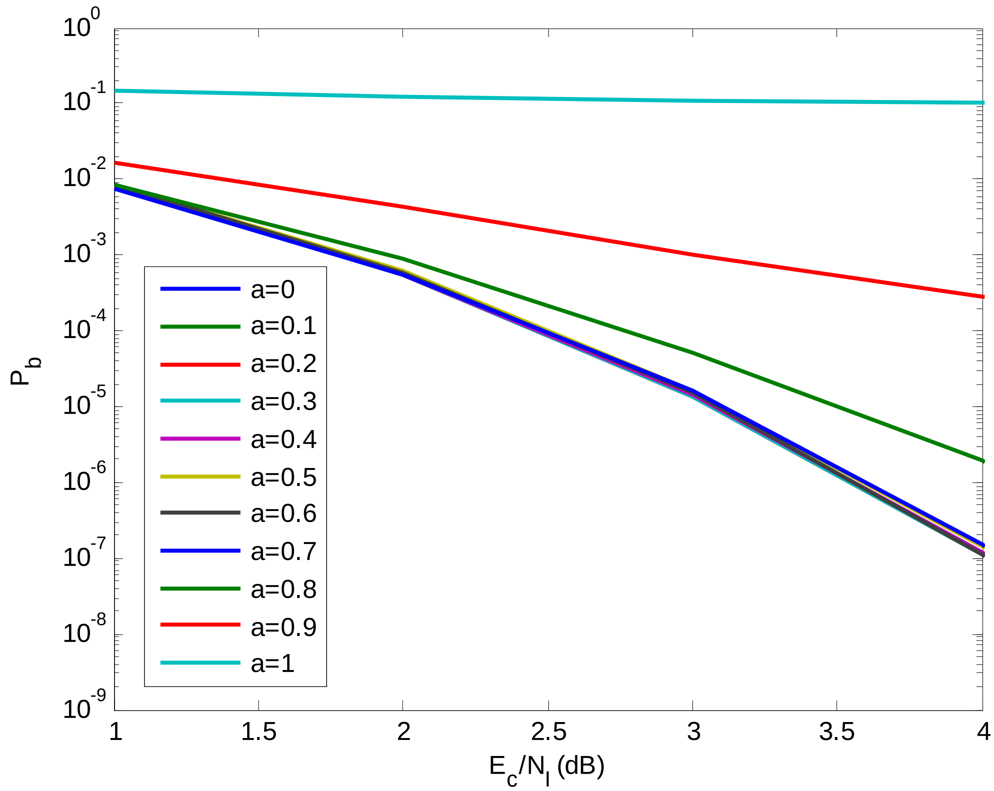

Figure 7. Performance of 32-ary orthogonal signaling with (31, 15) RS encoding and EED in AWGN plus PNI with ρ = 0.5 and E_C/N_O = 15 dB for different values of a.

In Figure 8, we see the performance of 32-ary orthogonal signaling with (31, 15) RS coding, EED and a diversity of two for $a = 0.6$ for different values of ρ with E_C/N_O = 3 dB. At $P_b = 10^{-5}$, there is about 1.7 dB difference in E_C/N_I between the best and worst performance. The best performance is when ρ = 1 with E_C/N_I = 7.8 dB. The worst performance is when ρ = 0.1 with E_C/N_I = 9.5 dB. The difference in performance is more obvious as E_C/N_O increases. This can be seen from Figure 9 where E_C/N_O = 15 dB. At $P_b = 10^{-5}$, there is 3.8 dB difference in E_C/N_I between the best and worst performance. The best performance is when ρ = 1 with E_C/N_I = 2 dB. The worst performance is when ρ = 0.1 with E_C/N_I = 5.8 dB. Therefore, while there is an improvement in absolute performance for a larger E_C/N_O, there is also a significant

increase in the relative performance gap between ρ = 1 and ρ = 0.1. For $0.4 < \rho < 1$, the performance is consistent as that shown for both figures; i.e., the performance improves as ρ increases and approaches 1.

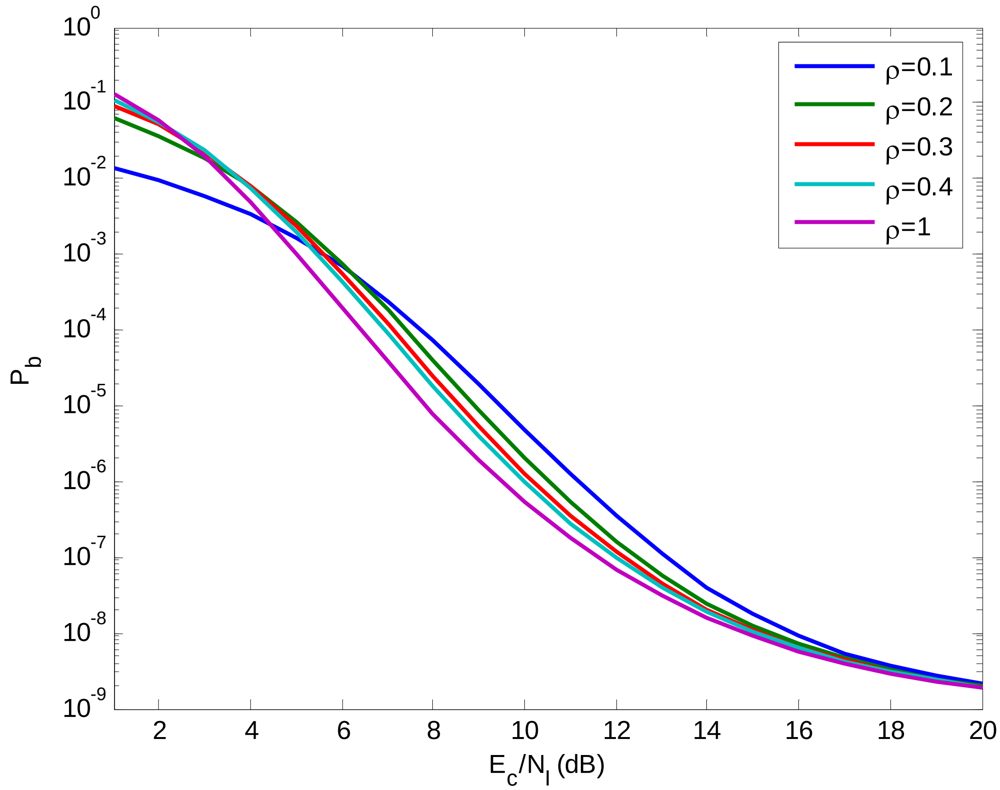

Figure 8. Performance of 32-ary orthogonal signaling with (31, 15) RS encoding and EED in AWGN plus PNI with a = 0.6 and E_C/N_O = 3 dB for different values of ρ.

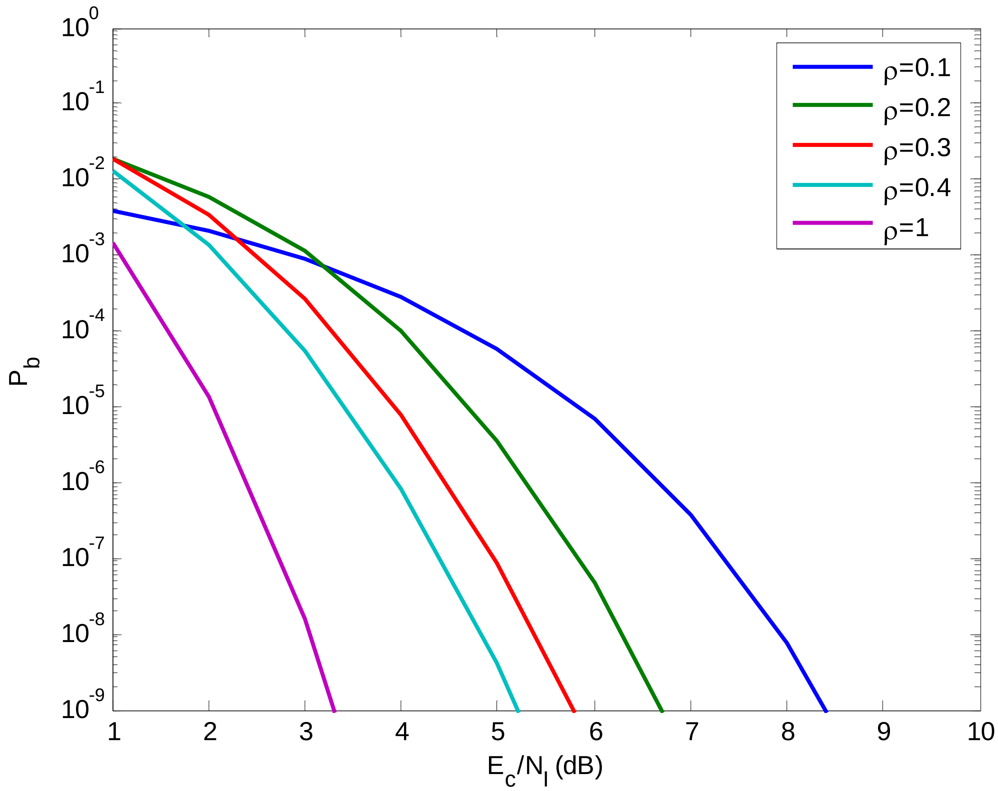

Figure 9. Performance of 32-ary orthogonal signaling with (31, 15) RS encoding and EED in AWGN plus PNI with a = 0.6 and E_C/N_O = 15 dB for different values of ρ.

The performance of 32-ary orthogonal signaling with (31, 15) RS coding, both with and without EED, for E_C/N_O = 3 dB and 15 dB are shown in Figures 10 and 11, respectively. In Figure 10, at $P_b = 10^{-5}$, for the various values of ρ shown, the performance with EED is inferior to that without EED by less than 1 dB. In Figure 11, with E_C/N_O increased to 15 dB, at $P_b = 10^{-5}$, for the various values of ρ analyzed, the performance with EED is inferior to that without EED by less than 0.2 dB. Thus, having EED does not improve the performance as compared to errors-only decoding, and the amount of degradation decreases with increasing E_C/N_O. This non-beneficial effect of using EED has also been observed in other similar researches on alternative JTIDS waveform as detailed in [10] and [11].

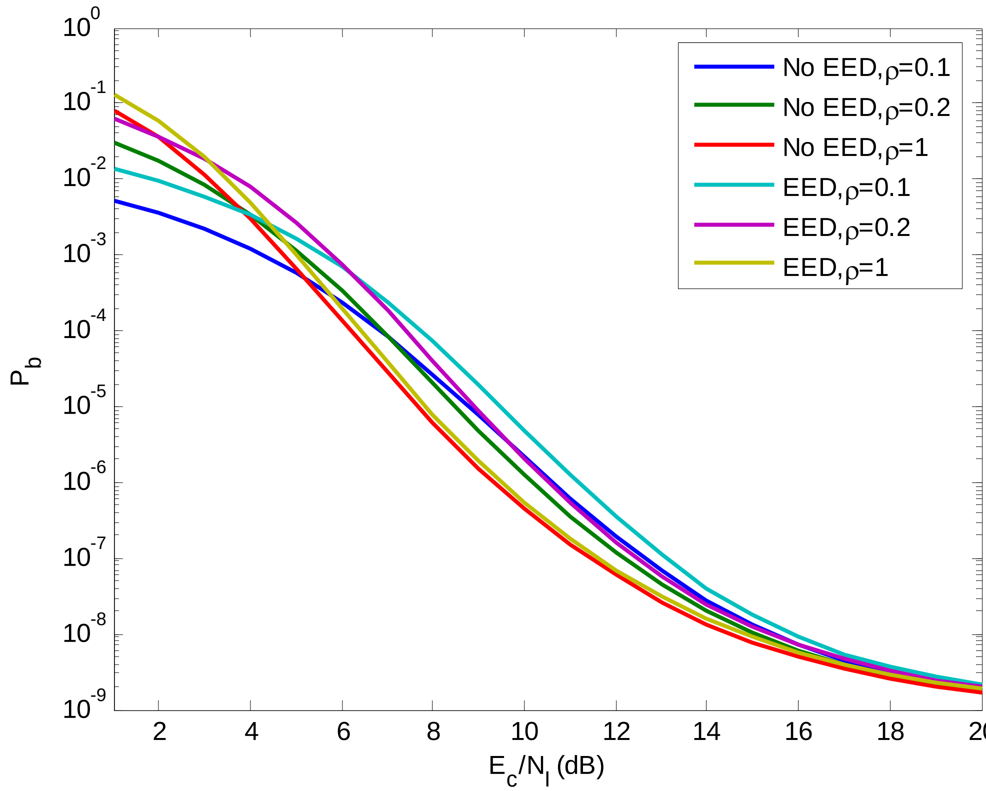

Figure 10. Performance of 32-ary orthogonal signaling with (31, 15) RS encoding with and without EED in AWGN plus PNI with $a = 0.6$ and $E_C/N_O = 3$ dB for different values of ρ.

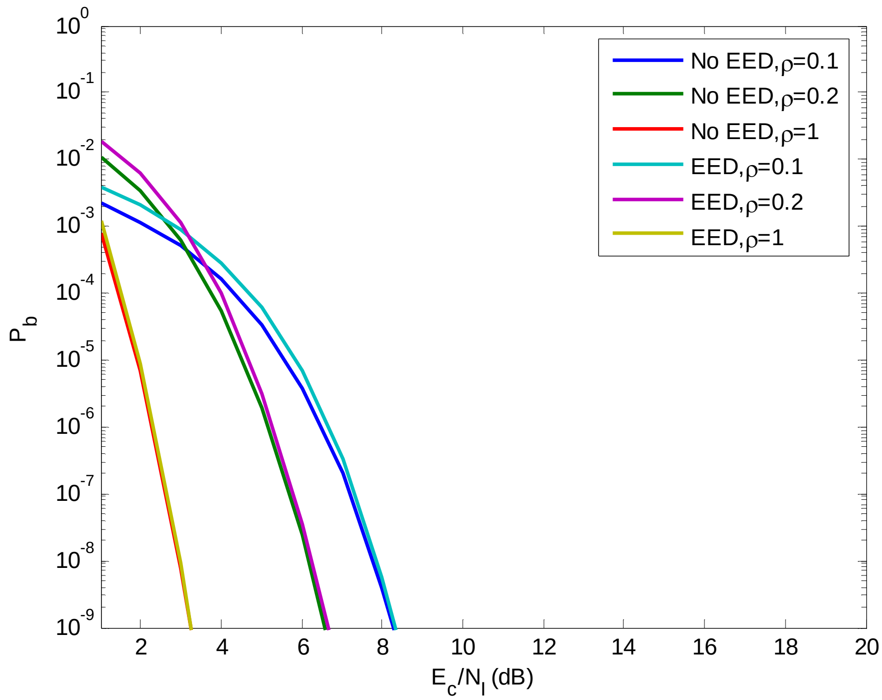

Figure 11. Performance of 32-ary orthogonal signaling with (31, 15) RS encoding with and without EED in AWGN plus PNI with $a = 0.6$ and $E_C/N_O = 15$ dB for different values of ρ.

D. PERFORMANCE IN AWGN AND PNI WITH PSI

The conditional probability of channel symbol error is given by (3.12), and the probability of channel symbol error with no diversity and in an AWGN environment is given by (2.6). For a system with PSI, when only one diversity reception is affected by PNI, the decoding decision is based on the diversity reception that is free from PNI. From (2.6), (3.12) and (2.12), the probability of channel symbol error with a diversity of two is

$$p_s = (1-\rho)^2 p_s(0) + 2\rho(1-\rho) p_s(1) + \rho^2 p_s(2) \tag{3.33}$$

where $p_s(0)$ is the conditional probability of channel symbol error when PNI is not present in either diversity reception and is expressed as

$$p_s(0) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{\left(\frac{-u^2}{2}\right)} \left\{ 1 - \left[1 - Q\left(u + \sqrt{\frac{4rmE_C}{N_O}} \right) \right]^{M-1} \right\} du. \tag{3.34}$$

where the RS code rate $r = 15/31$, $m = 5$ and $M = 32$.

The expression for the conditional probability of channel symbol error when only one of the diversity receptions suffers PNI (and is discarded) is the same as (2.6). This is because the PNI-affected pulse is discarded, leaving just the other pulse that is affected by AWGN only. Thus, (2.6), which was derived based on a single pulse in an AWGN environment can be used directly. Therefore, the conditional probability of channel symbol error when only one of the diversity receptions suffers PNI is given by

$$p_s(1) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{\left(\frac{-u^2}{2}\right)} \left\{ 1 - \left[1 - Q\left(u + \sqrt{\frac{2rmE_C}{N_O}} \right) \right]^{M-1} \right\} du. \tag{3.35}$$

Finally, the conditional probability of channel symbol error when both diversity receptions are affected by PNI is obtained from (3.12) as

$$p_s(2) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{\frac{-u^2}{2}} \left(1 - \left[1 - Q\left(u + 2\sqrt{\frac{2rm}{\frac{2}{\rho}\gamma_I^{-1} + 2\gamma_c^{-1}}} \right) \right]^{M-1} \right) du. \tag{3.36}$$

The performance of 32-ary orthogonal signaling with and without PSI for E_C / N_O = 5 dB and 10 dB are shown in Figure 12 and 13, respectively. For both cases of E_C / N_O, when ρ =1 there is no difference in performance whether PSI is used or not. This is logical since ρ = 1 implies that the channel is experiencing barrage jamming. For Figure 12, when E_C / N_O = 5 dB, at $P_b = 10^{-7}$ and for ρ = 0.2, E_C / N_I = 4.7 dB and 7.8 dB for PSI and no PSI, respectively. Thus, there is a gain of 3.1 dB with PSI for $P_b = 10^{-7}$. For $\rho < 0.2$ with PSI, $P_b < 10^{-5}$ even for very small values of E_C / N_I. In Figure 12, as E_C / N_I gets larger, the performance with PSI is worse as compared to that without PSI. This is because with PSI, discarding a weakly jammed pulse (i.e., high E_C / N_I) actually degrades performance. For Figure 13, when E_C / N_O = 10 dB, at $P_b = 10^{-6}$ and for ρ = 0.2, E_C / N_I = 5.5 dB for no PSI, whereas for PSI, $P_b < 10^{-6}$ even for very small values of E_C / N_I. For ρ = 0.1 with PSI, $P_b < 10^{-9}$ even for very small values of E_C / N_I.

From Figures 12 and 13, we see that for typical values of P_b (10^{-5} to 10^{-7}), there is a significant improvement in performance with PSI, regardless of the value of E_C / N_O, when $\rho < 1$. In contrast, we see that when PSI is not used, performance continues to degrade as ρ gets smaller.

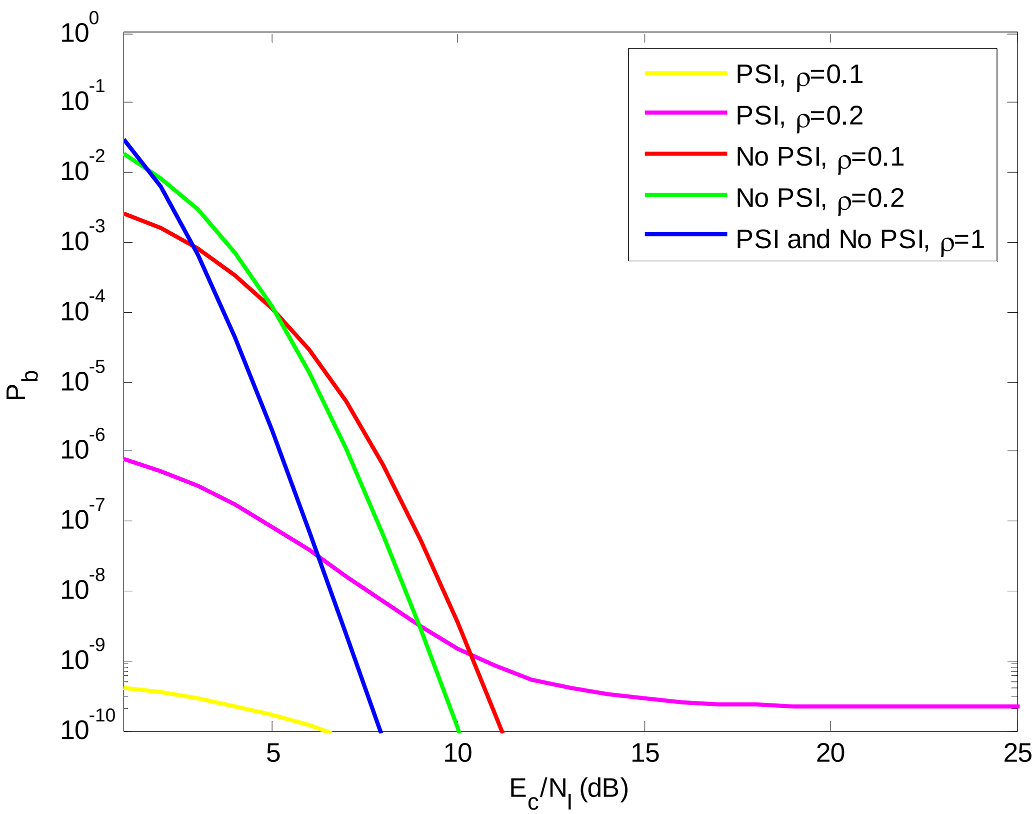

Figure 12. Performance of 32-ary orthogonal signaling with (31, 15) RS encoding with and without PSI in AWGN plus PNI with E_C/N_O = 5 dB for different values of ρ.

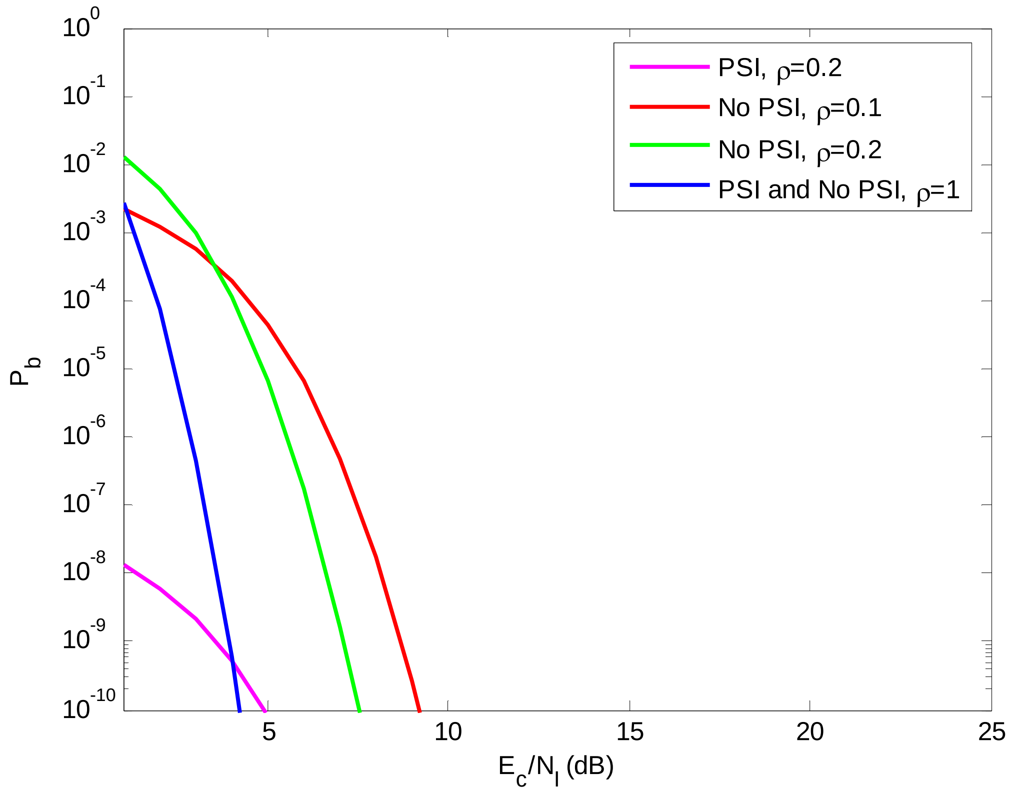

Figure 13. Performance of 32-ary orthogonal signaling with (31, 15) RS encoding with and without PSI in AWGN plus PNI with E_C/N_O = 10 dB for different values of ρ.

E. CHAPTER SUMMARY

In this chapter, the performance of the alternative JTIDS waveform with a diversity of two was investigated for both AWGN as well as AWGN plus PNI. The effect of either EED or PSI on the alternative JTIDS waveform in an AWGN plus PNI environment was also investigated. In an AWGN plus PNI environment, we saw that the alternative JTIDS waveform performs better when $\rho = 1$ (barrage noise interference) than when $\rho < 1$, but the performance is much better when $\rho \ll 1$ for typical values of P_b (10^{-5} to 10^{-7}). We also see that employing EED does not improve the performance of the receiver in both an AWGN and a PNI environment. The performance results with

PSI showed a significant improvement for a channel with AWGN and PNI when $\rho < 1$ for typical values of P_b (10^{-5} to 10^{-7}). In the next chapter, we compare the performance of the alternative JTIDS waveform with the original JTIDS waveform.

IV. COMPARISON OF THE ORIGINAL JTIDS WAVEFORM AND THE ALTERNATIVE JTIDS WAVEFORM

In Chapter III, the performance of 32-ary orthogonal signaling with (31, 15) RS coding was analyzed. In this chapter, the performance of the alternative JTIDS waveform and the original JTIDS waveform are compared. Detailed analysis of the original JTIDS waveform can be found in [5] and is not repeated here. The analysis from [5] is used to obtain the performance of the original JTIDS waveform where in this thesis coherent detection is assumed.

A. PERFORMANCE COMPARISON IN AWGN

The probability of information bit error for both the alternative and the original double-pulse JTIDS waveform is shown in Figure 14. At $P_b = 10^{-5}$, E_C/N_O = 1.7 dB and 4 dB for the alternative JTIDS waveform and original JTIDS waveform, respectively. This gives a 2.3 dB gain for the alternative JTIDS waveform as compared to the original JTIDS waveform. This gain can be attributed to the hard decision detection of the original JTIDS waveform as compared to the soft decision detection of the alternative JTIDS waveform.

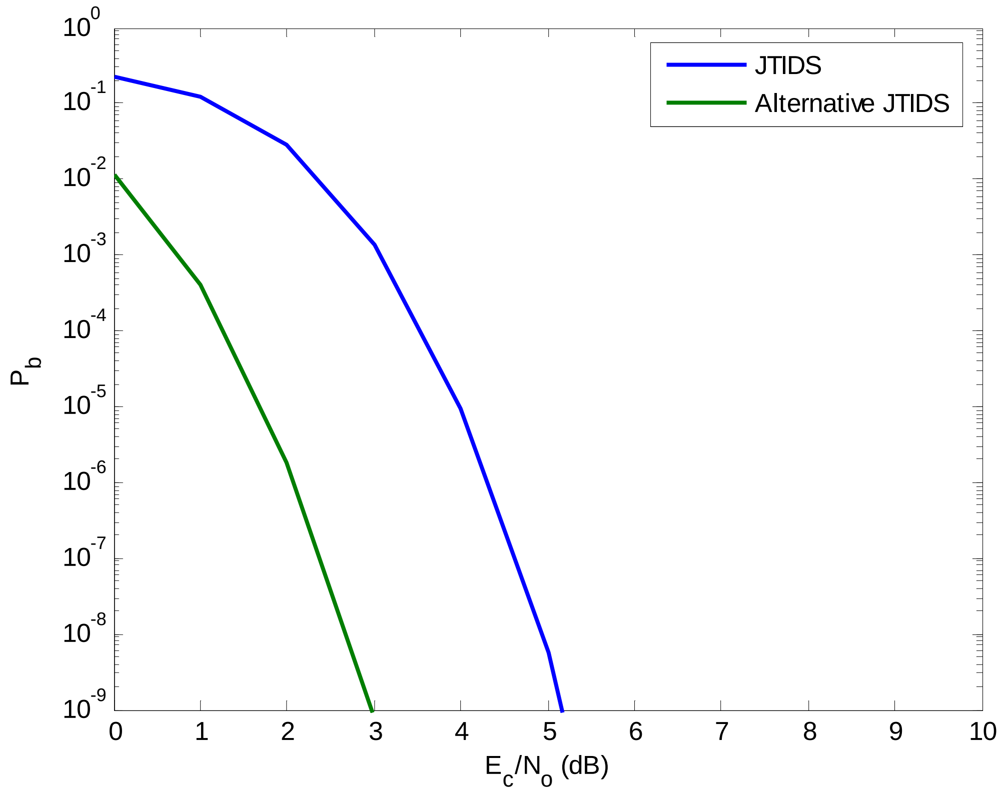

Figure 14. Performance of the alternative and the double-pulse original JTIDS waveform in AWGN.

B. PERFORMANCE COMPARISON IN AWGN AND PNI

The probability of information bit error for the alternative and original JTIDS waveform in AWGN and PNI, where the performance converges to 10^{-7} for $\rho = 0.1$, 0.2 and 1, is shown in Figure 15 for different values of ρ. For the plots to approach 10^{-7}, the alternative JTIDS waveform requires E_C/N_O of 2.5 dB, while the original JTIDS waveform requires a E_C/N_O of 4.8 dB. This gives a 2.3 dB gain for the alternative JTIDS waveform as compared to the original JTIDS waveform.

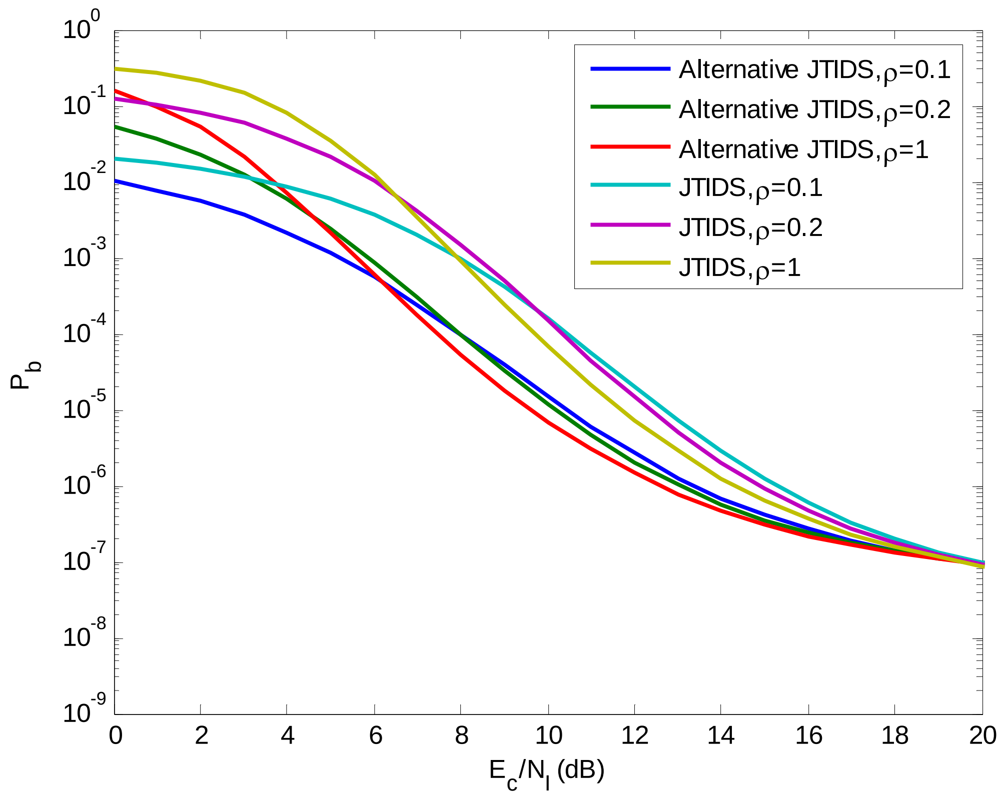

Figure 15. Performance of the alternative ($E_C / N_O = 2.5$ dB) and original JTIDS ($E_C / N_O = 4.8$ dB) waveform in AWGN and PNI.

At $P_b = 10^{-5}$, ρ = 1, the difference in E_C/N_I between the alternative (9.6 dB) and original JTIDS waveform (11.7 dB) is 2.1 dB. At $P_b = 10^{-5}$, ρ = 0.1, the difference in E_C/N_I between the alternative (10.5 dB) and original JTIDS waveform (12.7 dB) is 2.2 dB. For ρ = 0.2, the difference in E_C/N_I between the alternative (10.3 dB) and original JTIDS waveform (12.4 dB) is 2.1 dB. Thus, for the values of ρ considered, the alternative JTIDS waveform performs better than the original JTIDS waveform in AWGN and PNI.

In Figure 16, the case for the alternative JTIDS waveform and the original JTIDS waveform, both with E_C / N_O = 5 dB for ρ = 1, 0.2 and 0.1, is examined. At $P_b = 10^{-5}$, the alternative JTIDS waveform is superior to the original JTIDS waveform with a gain of 6.3 dB, 5.6 dB and 5.4 dB for ρ = 1, 0.2 and 0.1, respectively.

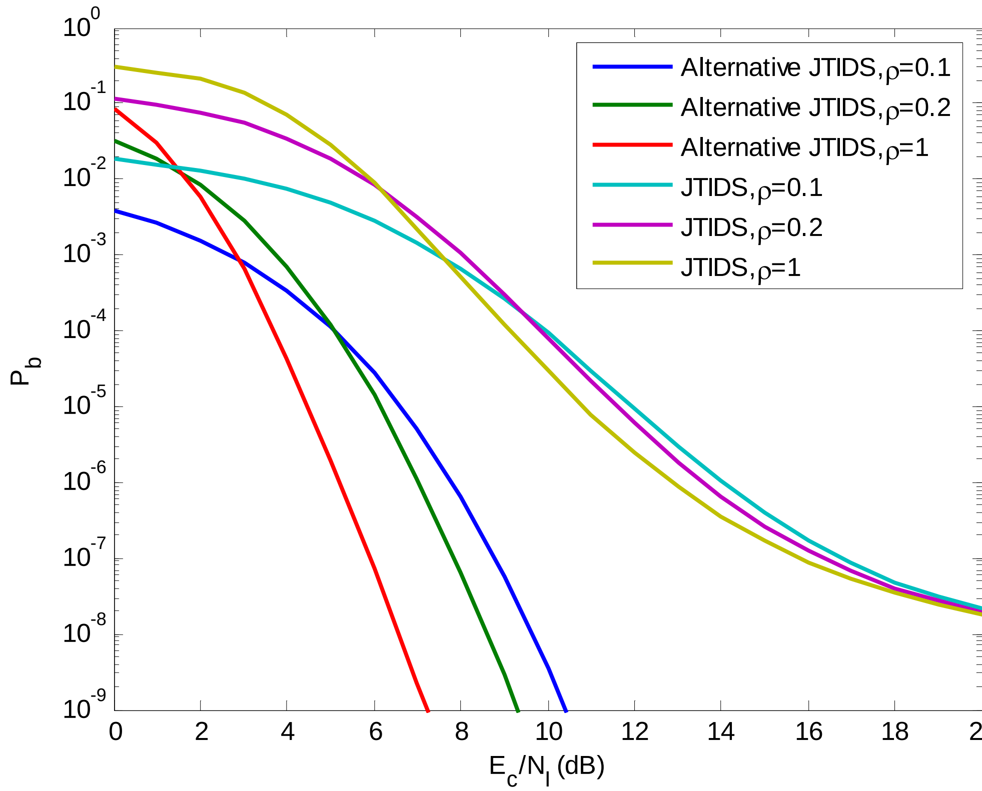

Figure 16. Performance of the alternative and the original JTIDS waveform in AWGN and PNI at $E_C / N_O = 5\,\text{dB}$.

From the above, when the performance for both the alternative and the original JTIDS waveforms converge to 10^{-7} for large E_C / N_I, we see that the alternative JTIDS waveform performs better than the original JTIDS waveform by about 2 dB at $P_b = 10^{-5}$ for all the value of ρ considered. For the case when E_C / N_O is the same for both the alternative and the original JTIDS waveforms, the alternative JTIDS waveform is superior as compared to the original JTIDS waveform.

C. PERFORMANCE COMPARISON WITH EED IN AWGN AND PNI

The performance of the alternative JTIDS waveform ($a = 0.6, E_C / N_O = 2.5\,\text{dB}$) and the original JTIDS waveform (threshold = 14, E_C / N_O = 4.4 dB) with EED, where the results all converge to $P_b = 10^{-7}$, are shown in Figure 17. For the alternative JTIDS

waveform to converge to $P_b = 10^{-7}$, E_C / N_O = 2.5 dB as compared to 4.4 dB for the original JTIDS waveform for a difference of 1.9 dB.

For ρ = 1, the alternative JTIDS waveform consistently outperforms the original JTIDS waveform for all values of E_C / N_I until the results converge at $P_b = 10^{-7}$. At $P_b = 10^{-5}$ and ρ = 1, the alternative JTIDS waveform has a gain of 1.5 dB over the original JTIDS waveform. For ρ = 0.2 and 0.1, the alternative JTIDS waveform barely outperforms the original JTIDS waveform by < 1 dB for typical values of P_b $(10^{-5}$ to $10^{-7})$. The reason for the disparity in the performance of the alternative JTIDS waveform between ρ = 1 and ρ < 1 is because, as shown in Chapter III, EED does not improve the performance for 32-ary orthogonal signaling with RS coding while there is an improvement in performance for the original JTIDS waveform with EED [5].

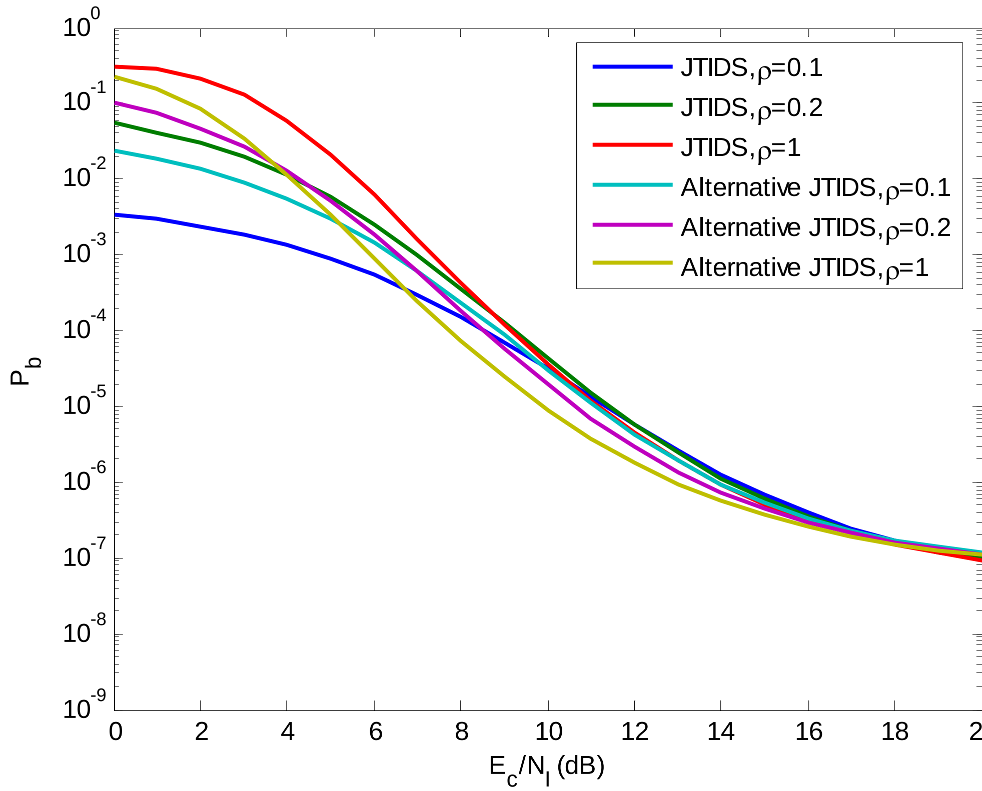

Figure 17. Performance of the alternative JTIDS waveform ($a = 0.6$, $E_C / N_O = 2.5$ dB) and the original JTIDS waveform (threshold = 14, $E_C / N_O = 4.4$ dB) with EED in AWGN and PNI.

In Figure 18, the case for the alternative JTIDS waveform and the original JTIDS waveform, both with $E_C / N_O = 5$ dB for ρ = 1, 0.2 and 0.1 is examined. At $P_b = 10^{-5}$, the alternative JTIDS waveform is superior to the original JTIDS waveform with a gain of 4.5 dB, 3.1 dB and 1.9 dB for ρ = 1, 0.2 and 0.1, respectively. The reason for the decreasing gain as ρ decreases is because, as shown in Chapter III, EED does not improve the performance for 32-ary orthogonal signaling with RS coding while there is an improvement in performance for the original JTIDS waveform with EED [5]. For typical values of P_b (10^{-5} to 10^{-7}), the alternative JTIDS waveform outperforms the original JTIDS waveform when both have the same E_C / N_O regardless of E_C / N_I.

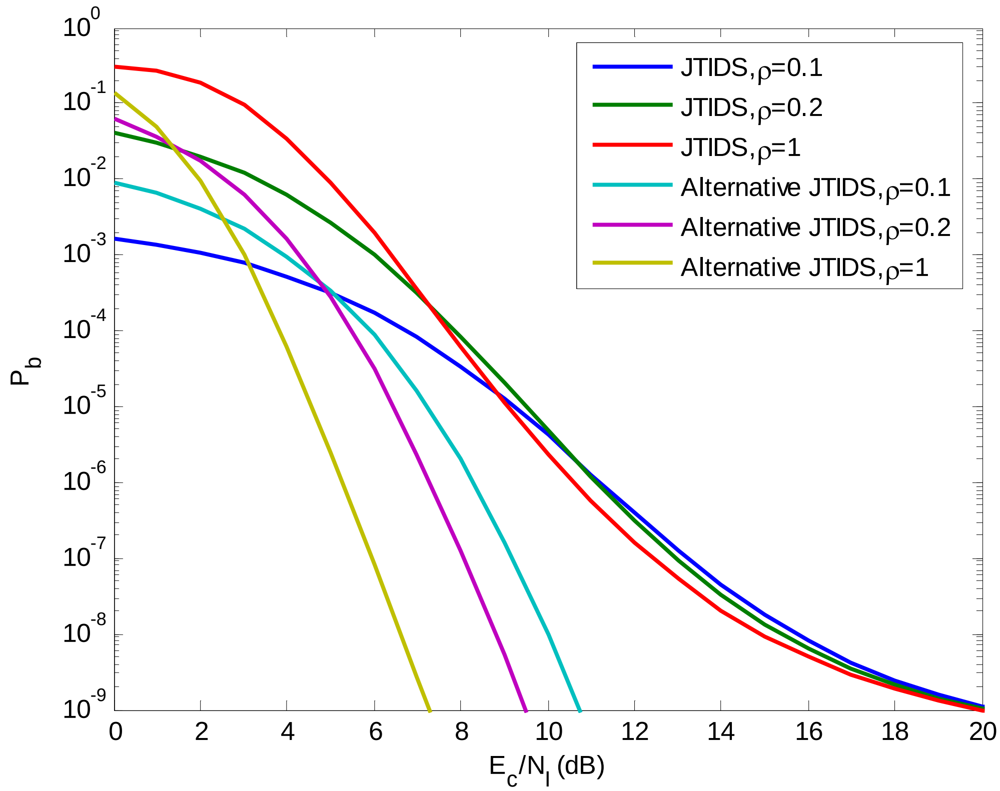

Figure 18. Performance of the alternative JTIDS waveform ($a = 0.6$) and the original JTIDS waveform (threshold = 14) with EED in AWGN and PNI at $E_C / N_O = 5$ dB.

D. PERFORMANCE COMPARISON WITH PSI IN AWGN AND PNI

The performance of the alternative JTIDS waveform with PSI is compared with that obtained for the original JTIDS waveform with EED in Figure 19 with $E_C / N_O = 5$ dB. At $P_b = 10^{-6}$ and for $\rho = 1$, the alternative JTIDS waveform shows an improvement of 5.4 dB over the original JTIDS waveform. At $P_b = 10^{-6}$ and for $\rho = 0.2$, $E_C / N_I = 11.1$ dB for the original JTIDS waveform, whereas $P_b \approx 10^{-6}$ for the alternative JTIDS waveform even for very small values of E_C / N_I. Thus, we can see that the alternative JTIDS waveform performs better than the original JTIDS waveform for all values of ρ and for typical values of P_b $(10^{-5}$ to $10^{-7})$.

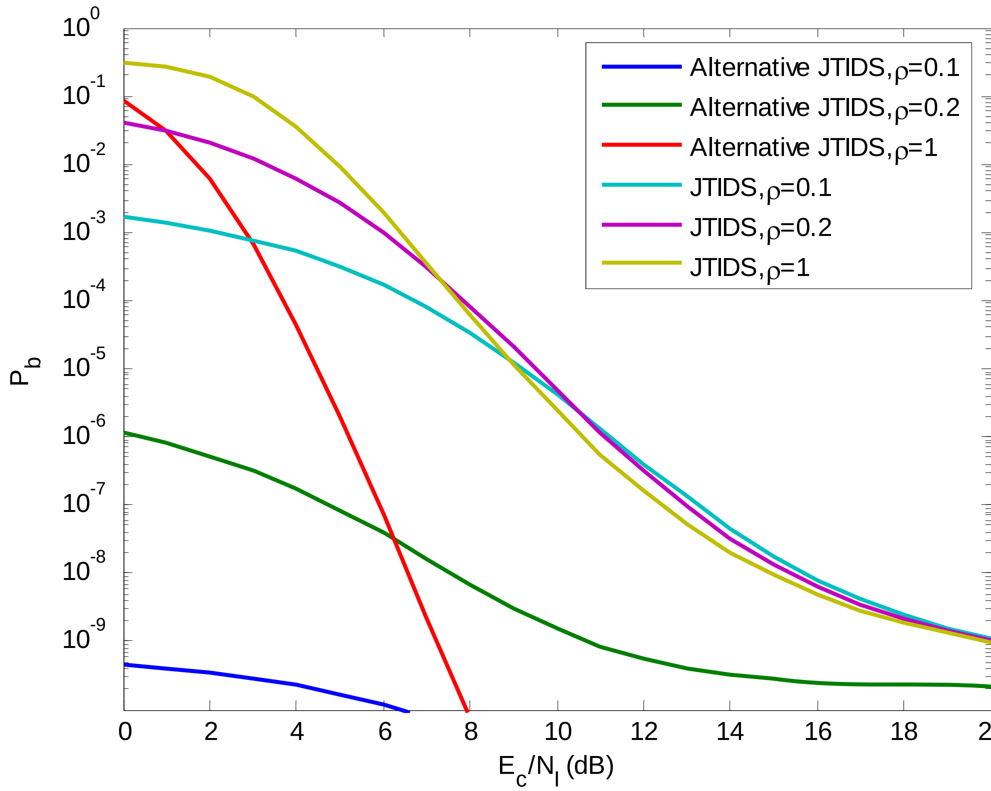

Figure 19. Performance of the alternative JTIDS waveform (PSI, E_C / N_O = 5 dB) and the original JTIDS waveform (EED, threshold = 14, E_C / N_O = 5 dB).

E. CHAPTER SUMMARY

In this chapter, the performance of the alternative and the original JTIDS waveforms in AWGN as well as AWGN plus PNI was compared. The results indicate that the alternative JTIDS waveform performs better than the original JTIDS waveform in an AWGN-only environment.

For an AWGN plus PNI environment, when the bit error rate performance for each system converges to 10^{-7} for high E_C / N_I, the results show that the alternative JTIDS waveform consistently performs better than the original JTIDS waveform for the values of ρ considered. Also, when E_C / N_O is the same for both waveforms, the alternative JTIDS waveform consistently outperforms the original JTIDS waveform for all values of ρ considered.

Next, the performance of the alternative JTIDS waveform with EED was compared to that of the original JTIDS waveform with EED in both AWGN and PNI. For the case when the performance of each system converges to 10^{-7} for high E_C / N_I, the results show that the alternative JTIDS waveform consistently outperforms the original JTIDS waveform for all E_C / N_I when $\rho = 1$. For $\rho < 1$, the alternative JTIDS waveform barely outperforms the original JTIDS waveform by < 1 dB for typical values of P_b (10^{-5} to 10^{-7}). The reason for this disparity in the performance of the alternative JTIDS waveform between $\rho = 1$ and $\rho < 1$ is because, as shown in Chapter III, EED does not improve the performance for 32-ary orthogonal signaling with RS coding while there is an improvement in performance for the original JTIDS waveform with EED [5]. Also, when E_C / N_O is the same for both waveforms, the alternative JTIDS waveform outperforms the original JTIDS waveform for typical values of P_b (10^{-5} to 10^{-7}).

Finally, the performance of the alternative JTIDS waveform with PSI was compared to that of the original JTIDS waveform with EED in both AWGN and PNI. The results show that the alternative JTIDS waveform consistently outperforms the original JTIDS waveform for typical values of P_b (10^{-5} to 10^{-7}).

In the next chapter, the conclusions reached as a result of the analyses in Chapters III and IV are summarized and future research areas are recommended.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

An alternative JTIDS waveform, 32-ary orthogonal signaling with (31, 15) RS coding, was presented in this thesis. The performance of the alternative JTIDS waveform (with a diversity of two) was analyzed and its performance was compared with that of the existing JTIDS waveform (double-pulsed structure; i.e., a diversity of two). The effect of errors-and-erasure decoding and perfect-side information for channels with AWGN only as well as AWGN plus PNI were also investigated.

Based on the results obtained, the alternative JTIDS waveform with 32-ary orthogonal signaling and (31, 15) RS coding was found to perform better than the original JTIDS waveform in an AWGN-only environment (Chapter IV, Section A). At $P_b = 10^{-5}$, the alternative JTIDS waveform has a 2.3 dB gain as compared to the original JTIDS waveform. In an AWGN plus PNI environment, the results show that the alternative JTIDS waveform consistently performs better than the original JTIDS waveform for all the values of ρ considered and for typical values of P_b (10^{-5} to 10^{-7}) (Chapter IV, Sections B and C). In AWGN and PNI, when $E_C / N_O = 5$ dB for both waveforms, at $P_b = 10^{-5}$, the alternative JTIDS waveform is superior to the original JTIDS waveform with a gain of 6.3 dB, 5.6 dB and 5.4 dB for $\rho = 1$, 0.2 and 0.1, respectively.

We also found no benefit to using EED for the alternative JTIDS waveform since it does not improve the performance as compared to errors-only decoding (Chapter III, Section C). Also, with EED and for $\rho < 1$, the alternative JTIDS waveform barely outperforms the original JTIDS waveform by < 1 dB for typical values of P_b (10^{-5} to 10^{-7}). This result is rather surprising since EED often improves the performance of a waveform when PNI is present. We have also shown that with PSI, the alternative JTIDS waveform performs significantly better than the original JTIDS waveform with EED (Chapter IV, Section D). At $P_b = 10^{-6}$ and $\rho = 1$, the alternative JTIDS waveform shows an improvement of 5.4 dB over the original JTIDS waveform and the gain improves for $\rho < 1$.

B. FUTURE RESEARCH AREAS

We have examined an alternative JTIDS waveform that consists of 32-ary orthogonal signaling with (31, 15) RS coding and provides an improvement over the original JTIDS waveform.

In this thesis, only coherent demodulation was considered. Possible follow-on work could be to extend this thesis to non-coherent demodulation. Further research work could also be done to investigate why EED does not improve the performance of the alternative JTIDS waveform. The performance of the original JTIDS waveform may be further improved by using a concatenated code, specifically, a RS code as the outer code and a non-binary convolutional code as the inner code. Another possible follow-on research area could be to examine and analyze the alternative JTIDS waveform for a fading channel. Finally, different RS code rates could be considered to trade off bit error rate robustness against data rate.

LIST OF REFERENCES

[1] Dr. Carlo Kopp, "Network Centric Warfare Fundamentals – Part 3" [Online]. http://www.ausairpower.net/NCW-101-3.pdf.

[2] Michael B. Pursley, Thomas C. Royster, IV, and Michael Y. Tan, "High-Rate Direct-Sequence Spread Spectrum," *Proc. IEEE MILCOM*, vol. 2, pp. 1101-1106, Clemson University, SC, October 2003.

[3] Michael B. Pursley, and Thomas C. Royster, IV, "High-Rate Direct-Sequence Spread Spectrum With Error-Control Coding," *IEEE Transactions on Communications,* vol. 54, pp. 1693-1702, September 2006.

[4] Hua Wang, Jingming Kuang, Zheng Wang, Hui Xu, "Transmission Performance Evaluation of JTIDS", *Proc. IEEE MILCOM*, vol. 4, pp. 2264 – 2268, October 2005.

[5] Chi-Han Kao and C. Robertson, "Performance Analysis of a JTIDS/Link-16-type Waveform Transmitted over Nakagami Fading Channels with Pulsed-Noise Interference," *Proc. IEEE Military Commun. Conf., 2*008.

[6] R. C. Robertson, class notes for EC4550 (Digital Communication), Naval Postgraduate School, Monterey, California, 2007 (unpublished).

[7] R. C. Robertson, class notes for EC4550 (Sequential and Parallel Diversity), Naval Postgraduate School, Monterey, California, 2007 (unpublished).

[8] R. C. Robertson, class notes for Frequency-Hopped Spread Spectrum, Naval Postgraduate School, Monterey, California, 2007 (unpublished).

[9] R. C. Robertson, class notes for EC4580 (Error Correction Coding), Naval Postgraduate School, Monterey, California, 2007 (unpublished).

[10] Cham Kok Kiang, "Performance Analysis of an Alternative Link-16/JTIDS Waveform Transmitted Over a Channel with Pulse-Noise Interference", Master's thesis, Naval Postgraduate School, Monterey, California, 2008.

[11] Dimitrios Lekkakos, "Performance Analysis of a Link-16/JTIDS Compatible Waveform Transmitted Over a Channel with Pulse-Noise Interference", Master's thesis, Naval Postgraduate School, Monterey, California, 2008.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Professor Jeffrey B. Knorr, Chairman
   Department of Electrical and Computer Engineering
   Naval Postgraduate School
   Monterey, California

4. Professor R. Clark Robertson
   Department of Electrical and Computer Engineering
   Naval Postgraduate School
   Monterey, California

5. Assistant Professor Frank Kragh
   Department of Electrical and Computer Engineering
   Naval Postgraduate School
   Monterey, California

6. Richard North, Technical Director for JTRS
   JPEO JTRS
   San Diego, California

7. Howard Pace, Deputy Program Executive Officer for JTRS
   JPEO JTRS
   San Diego, California

8. Captain Steven McPhillips
   Program Manager, Command and Control Systems (PMW 150)
   PEO C4I
   San Diego, California

9. Captain John Pope
   Program Manager, Communications Systems (PMW 170)
   PEO C4I
   San Diego, California

10. Donna Miller, Research Associate
Department of Electrical and Computer Engineering
Naval Postgraduate School
Monterey, California

11. Professor Yeo Tat Soon, Director
Temasek Defence Systems Institute
National University of Singapore
Singapore

12. Tan Lai Poh (Ms), Assistant Manager
Temasek Defence Systems Institute
National University of Singapore
Singapore

13. MAJ Ho Kah Wei
Republic of Singapore Air Force
Singapore